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The deep notch four point bend test.

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THE DEEP NOTCH FOUR POINT BEND TEST

BY

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ABSTRACT

In a previous work at Lehigh University a fracture toughness weldment test using a four point bend loaded specimen was developed. The present work extends this test development by redesigning the test specimen configuration so that fracture toughness data can be obtained from the test results. The original specimen had a hard crack-starter weld bead, which during this study, was found to be difficult to control in order to obtain a consistent sharp crack in the desired position in the specimen. Moreover, the small size of the natural crack produced by the bead required the use of high load to fracture, in most cases above those for general yielding. This led to inexactness in fracture behavior analysis. In order to solve this difficulty, a combination of a mechanical notch and a hard metal weld plug was developed; this simple design led to a surface crack with a semi-elliptical shape. This notch configuration, with the appropriate instrumentation, permitted fracture toughness calculations and produced fractures at applied loads below the yield point. The fracture toughness measurements obtained, when compared with values given in the literature for the same materials, are in a reasonable agreement.

INTRODUCTION

A welded plate is a composite structure containing many kinds of defects, as well as having residual stresses as a result of the weld solidification and shrinkage process. It is known that the metallurgical and mechanical properties of some parts of the composite are different and may change according to the different heat and mechanical treatments they receive. This property variation can produce a related marked variation in fracture behavior. For example, a crack running in a brittle HAZ region may be stopped by the better properties of the material beyond this region. Alternately, it may remain within this brittle region, usually within 3 mm of the fusion line, and produce a complete brittle fracture. A. A. Wells pointed out in 1964 that "The complexity of this situation presents a challenge in defining suitable procedures for the qualification of welded structures." Many attempts have been made to meet this challenge and the literature records a number of weldment fracture tests,[1-6] yet Dr. Wells' statement concerning the challenge of finding a suitable test procedure is still, in many respects, as valid today as it was in 1964.

Fracture toughness tests usually follow one of two approaches.

(a) Testing of small samples from every part of a weldment.[2,7,8]

(b) Testing a full weldment of sufficient size to mirror the fracture behavior of the weldment in service.[4,5,6]

Previous work at Lehigh University, from which the current program developed[9] centered on the latter type of test. The full weldment test must, of necessity, be large and testing to fracture, especially in tension, may present some practical problems. Thus the work at Lehigh University was directed to the development of a bend specimen, which, while not as easy to analyze as the tension test, allowed for much lower loads in testing and subsequent testing of much larger specimens. In this development a four point loaded bend specimen was explored. A width to length dimension was selected so as to give 2:1 biaxial stress ratio in the plate center[9,10,11] while retaining manageable specimen size. This gave plate dimensions of 457 mm x 228 mm x 25 mm. It was found in this work that the loading points, which were initially rigid rounded parts, were introducing friction effects in the test. W. F. Brown and J. E. Srawley[12] had found that free rolling load points were necessary to bring calculated stresses in four point bending in line with experimental results because high friction forces, especially when the plate yield point is exceeded , produce tension as well as bending in the specimen. Thus the test jig with rolling load points, seen in Figure 1, was developed.

The crack starter configuration used in this specimen was that shown in Figure 2. This was essentially a hard facing weld bead (Hardex N) which could crack on loading and produce a maze of sharp ended cracks which have a high probability of having at least one in the most brittle region of the weld. Several steels were tested using this procedure with the results being reported in reference 9. This last requirement was an important one because, in accordance with the work of J. J. W. Nibbering[1] on weldment tests, the position and orientation of a crack tip in a weldment appears to have more influence on the fracture behavior than crack length.

As will be described later, the test appeared to have some strengths and weaknesses and this second program on test development is the result. The main purpose of this program was to center on the use of the test to provide quantitative fracture toughness information on the plates and weld zones tested. This is a complex problem because, as a number of investigators[1,3,15] have indicated fracture often occurs not under low stress plain strain conditions but after general yielding. This is not an insurmountable problem in testing, however, because as F. M. Burdekin[16] has indicated "For an assessment of resistance to fracture initiation, tests should be carried out on samples representative of parent material, heat affected zone and weld metal. The test can either set out to measure plane strain fracture toughness (K_{1C}) or crack opening displacement (COD) to fracture. These two approaches are compatible, plane strain fracture toughness being relevant below a transition temperature and critical COD in and above the transition. Clip gauge instrumentation can be used in both cases."

The rest of this document will detail attempts to make such measurements on four point bend test specimens. The main points of attack on this problem were:

(1) To define and control the crack starter configuration and

(2) To add the instrumentation and analytical procedures which could allow calculation of COD or K_{1C} from the test results.

Subsequent sections will deal with these specific areas of investigation.

EXPERIMENTAL WORK AND DISCUSSION

As the experimental work on the four point bend test was originally conceived, it was intended that a large number of random cracks would be produced in the "standard" crack starter bead. For the plain plate tests (i.e. without weldments), this philosophy appeared to be relatively successful in that brittle failures occurred at temperatures below a given transition temperature while above it, no fracture occurred even in the presence of extensive bending. Some preliminary tests with weldments of A285C (a low toughness normalized plain carbon steel) and A543 (a high toughness quenched and tempered alloy steel) described in reference (9), however, produced mixed results. The A543 bend tests gave results consistent with Charpy impact behavior while the A285C tests did not. The experimental work undertaken and described here was to understand this behavior and modify the test as required.

A. WELDED PLATE TESTS AND THEIR SIGNIFICANCE TO THE TEST SPECIMEN DESIGN

In order to study the ability of the Four Point Bend Test to seek out and numerically characterize the lowest toughness zone of a weldment, a series of submerged arc welded specimens of A-537 Class 1 Steel, welded with Armco W-19 (3.5% Ni) 4 mm wire and Linde 0091 flux were tested. Chemical composition for these materials is given in Table 1. The purpose of this series was to produce data on specimens welded with two different conditions:

(a) High heat input: 6 KJ/mm

(b) Low heat input : 2 KJ/mm

The weldments were made from the previously tested A-537 heat, which results are reported in reference (9) and are shown in Table 2. Charpy impact test results for the base plate, heat affected zone, and weld metal, for both conditions, are detailed in Table 3. The specimens were tested with the "Standard Procedure" described in reference (9) and the results are summarized in Table 4.

Analysis of the results reported in Table 4, along with an analysis of the fractured specimens revealed:

(a) None of the plates broke in the heat affected zone or weld metal.

(b) There was considerable deflection before breaking.

(c) The strain pattern of the specimens tested in the as-welded condition and those tested with the reinforcement removed was undoubtedly different.

(d) During fracture, the crack propagation was in two steps. Initially propagation was in the transversal direction and after the crack had reached both edges the total fracture occurred.

These results together with those reported in reference (9), suggested that during bending in most cases at "practical" temperatures extensive plastic yielding may occur. This was not surprising since the test reflects "the real conditions" and T. Kanazawa, et al.,[3] have pointed out that "in most of in-service brittle failures of ordinary welded steel structures, defects that lead to catastrophic failure are located at or near a welded joint and/or structural discontinuity where high stress and strain concentrations exist. This implies that a majority of brittle fracture initiation in ordinary welded steel structures would occur under large scale yielding."

Also in the case of the A-537 submerged arc weldment, during testing, failures were always induced in the base plate either just beyond the heat affected zone or well into the plate. No weld metal failures occurred in the high heat input weldment, and this is somewhat surprising as the high heat input weld metal absorbed 27 J at the failure transition temperature -30°C while the base plate absorbed at least 68 J at these temperatures. Charpy impact data is given in Appendix 1. Moreover, the heat affected zone (coarse grained region) absorbed about 88 J and the actual region where half of the fractures actually occurred in the low heat input weldment absorbed 95 J at the fracture transition temperature. Thus it appears that plastic yielding effects were important.

In order to better understand the last results, simple strength of materials concepts may be applied. The welded plate is considered as an idealized composite material (Figure 3) and the three plate components are assumed to have different mechanical properties. It was also assumed that:

$$\sigma_{YS_{M_3}} > \sigma_{YS_{M_2}} > \sigma_{YS_{M_1}} \qquad (1)$$

where $\sigma_{YS_{M_3}}$ = Weld metal yield strength

$\sigma_{YS_{M_2}}$ = Heat affected zone yield strength

$\sigma_{YS_{M_1}}$ = Base plate yield strength

Under these conditions, the stress distribution during bending elastically of an uncracked composite plate is as shown in Figure 4 and the stresses are given by:[17]

$$\sigma_{ZZ} = \frac{6\ P\ L_1}{w\ t^3} \left(\frac{t}{2} - y\right) \tag{2}$$

where P = Applied load

L_1 = (outer span - inner span)/2

W = Width

t = Thickness

(Details of these equations are given in Appendix 2) and the stresses for the outer tension fiber (Y=0) by

$$\sigma_{ZZ} = \frac{3\ P\ L_1}{w\ t^2} \tag{3}$$

There is a load P = Pa, such that when applied, the outer tension fibers start plastically deforming. At this moment:

$$\sigma_{ZZ} = \sigma_{YS}$$

and

$$\sigma_{YS} = \left(\frac{3\ L_1}{w\ t^2}\right) Pa \tag{4}$$

For the composite material:

$$Pa_1 < Pa_2 < Pa_3 \tag{5}$$

During bending, as the load increases, Pa_1 is reached and the material M_1 (base plate) starts yielding while M_2 and M_3 are still deforming elastically. This is shown in Figure 5.

Figure 5a shows a Four Point Bend Test specimen bent with the reinforcement intact and Figure 5b with the reinforcement removed. The above analysis led to the concept that a brittle fracture in the least tough of the three components of the composite material will not occur unless plane strain fracture toughness is reached before any of the components starts yielding. If yielding occurs the fracture can be prejudiced into the area which has the most strain, in this case in M_1 (assuming that strain hardening effects are not important and that in each component there is a crack producing the same effect without interaction with the others). In order to obtain a brittle fracture it would be necessary to test the plate at lower temperatures (which increase the yield strengths of the three regions) or/and changing the initial crack dimensions, to produce fracture at lower stresses.

Excessive yielding in the plates also had an influence on the overall strain patterns in the specimens as well. It had been observed that either for the unwelded plate or for the welded plates, the specimens broke close to the ends of the 76 mm long crack starter bead, i.e. Figure 6. According to reference (9) the longitudinal strain increases from the center of the plate to the inner rolls contact point, that means that the ends of the crack starter are subjected to a higher strain than the center. Therefore if the plates were tested with a relatively sound crack starter bead and with the higher strain results, the strain would force the crack starter to break in that zone. The test thus again fails because of excessive strains required to produce fracture. To remove this difficulty, the stresses to failure must be reduced by some means.

B. CHANGING THE CRACK STARTER BEAD

The Hardex-N crack starter has served as a natural crack producer but cracking was not always uniform. Moreover crack starter bead dimensions appeared to be too small to produce low stress failure. Thus, the search was turned toward larger flaw sizes in the specimens by using either a larger crack starter bead, a mechanical notch or both in combination. Initially, an extended crack starter bead up to 40 mm in width was employed. Examples of such beads are seen in Figure 7. Tests of this type, performed at low temperature on several steels were not satisfactory. The cracked region across the multiple starter beads appeared to be irregular, producing an indeterminate crack starter condition as far as fracture toughness calculations were concerned. The main problem found however was that the natural cracks produced in the crack starter bead were not uniform (fracture in the crack starter bead is produced by the effect of applied stresses over its defects) so that, in fact, the probability to have a crack in the weakest part of the specimen was reduced by increasing the defect size in the crack starter bead. Moreover, when several cracks appeared, the effect of the individual crack was reduced by the crack interactions. As pointed out by Peterson[18] the effect of a single crack is worse than several cracks. As can be seen in Figure 8 the effect of a single crack decreases, as the distance between cracks decreases.

A correction of this condition was attempted using a "starter notch" in the hard facing to control the natural crack position. However the fracture path, as seen in Figure 7a, did not always follow the preplaced notch. Indeed fracture surface examination revealed that the crack started to propagate from a welded defect, not the starter notch induced crack.

Finally, no significant change in the applied load to fracture, with respect to the initial crack starter bead width was observed. An analysis of the results of these experiments led to the conclusion that:

(a) It is necessary to have the starter cracks in the right position.

(b) The possibility of testing the full weldment is reduced by the difficulty for controlling the number of cracks and their interactions.

On the past-time side, these tests did reveal the characteristics that are required of the starter cracks. These may be summarized as follows:

(a) As the four point bend is a "crack initiation" test, the sharp crack should be preferably obtained at room temperature and with as low a load as possible.

(b) The flaw-position should be controlled within a range of a few millimeters to find the zone of interest.

(c) The flaw should have a simple shape which would permit fracture mechanics analysis.

C. DEEP NOTCHED FLAW TEST

Since the natural crack alone did not produce satisfactory results, the mechanical notch was explored as an accurate and positive method for ensuring starter cracks in the right regions. Therefore, excluding the possibility of fatigue precracking because of the "simple nature" of the test, and considering that if residual stresses are present it is not always possible to produce easily uniform fatigue crack fronts in as-welded test pieces, a special design to produce these crack-notches was developed and is shown in Figure 9. A specimen of the standard configuration (230 x 460 x 25) was slotted using a 75 mm dia. cutter to the center thickness of the plate. The machined in slot was about 75 mm long and was oriented transverse to the long axis of the specimen. A shallow hole, 12.5 mm in diameter and 3.5 mm deep, was drilled at either end of the slot and filled with a Hardex-N plug weld. Because of the presence of the slot over which the weld was placed, the Hardex-N cracked (in most cases at room temperature, before bending) and extended the machined notch at each end by the diameter of the weld bead. The final flaw was then approximately 80 mm long. This specimen design was successful in producing fractures at low stresses and specific weld regions. Moreover, the preliminary tests suggested that a measurement of the crack opening displacement might be possible and that a relation similar to those found in the literature[1,3,16,19] could be applied to this specimen. Moreover, the simple shape of the notch allowed application of a Stress Intensity Factor determined by A. S. Kobayashi et al.[14] to the test thus, leading to the potential for calculation and measurement of the Plane Strain Fracture Toughness values from the test.

1. <u>Fracture Mechanics Calculations</u> - <u>Plane Strain Fracture Toughness</u>

When considering the fracture of a four point bend specimen, by applying linear elastic fracture mechanics concepts, it is necessary to account for:

(a) The fracture toughness of the crack starter (plug weld in the notched specimen).

(b) Fracture toughness of the specific region of specimen (fracture toughness of the weld metal, HAZ and base plate).

No experiments have been made in order to determine the K_{1C} of the Hardex-N, because of its brittle nature. The microstructure after cooling (the specimen is big enough to rapidly cool the weld plug) is mostly fresh martensite. Besides it was expected to have micro cold-cracks, slag inclusions and other kinds of defects that provide the required flaw for further cracking.

To determine the fracture toughness of the specimen it was necessary to assume the following:

(a) There was an initial crack.

(b) The crack has a semi-elliptical shape.

(c) There was a crack in the right position, i.e., in the zone of interest.

The authors in reference (14) have given a solution for the stress intensity factor of a semi-elliptical flaw in a half-space subjected to linearly varying load. The curves for the stress intensity magnification factor are given in Figure 10. The stress intensity factor, as given in reference (14) and applied to the four point bend test, may be calculated from:

$$K_1 = M_B \frac{3\,P\,L_1}{W\,t^2} \frac{\sqrt{\pi\,b}}{E(k)} \left(\sin^2\theta + \frac{b^2}{a^2}\cos^2\theta \right)^{1/4} \qquad (6)$$

Where:

K_1 = Stress intensity factor

M_B = Stress intensity magnification factor

P = Applied load

L_1 = (Outer span - Inner span)/2

W = Specimen width

t = Specimen thickness

b = Notch depth

$2a$ = Crack length

$E(k)$ = Complete integral of the second kind

(The development of equation (6) is given in Appendix 3.) Analysis of the curves given in Figure 10 shows that for any b/a relation, at lower values of the angle θ (i.e., close to the surface) the stress intensity magnification factor can be considered relatively constant and equal to $M_B = 0.9$. Indeed, for specimens tested with this notch, this was confirmed by the experimental observation of the specimen fracture surface pattern. The crack seems to initiate close to the surface, so that without introducing an appreciable error the angle θ could be considered equal to 10 degrees ($\theta = 10°$). Applied loads were measured during the tests.

2. Fracture Mechanics Calculations - Crack Opening Displacement Approach

Crack Opening Displacement concepts have been introduced to provide fracture toughness measurements in conditions of greater ductility where linear elastic fracture mechanics becomes invalid.[2,19] "The object of the test is to determine the value of the critical crack opening displacement (COD) at the tip of a defect at the onset of crack extension."[19] This displacement is calculated from opening face of the crack.

An empirical relationship for the Crack Opening Displacement with the displacement of the two edges of the notch, recorded by means of a clip gauge, was determined. The relationship was derived by assuming a hinge mechanism about a center of rotation in the specimen. The location of the pivot depends on the applied load, and a rotational factor "r", which can be experimentally determined.[3] The value "r" is taken in the literature, most commonly to be 1/3 (r = 1/3). Experimental clip gauge readings could then be reduced to COD values using a simple proportionality relation, obtained from Figure 11 and given by:

$$\frac{V_c}{\delta} = \frac{a + r\ (w-a)}{r\ (w-a)} \qquad r = 1/3$$

$$\delta = V_c \frac{(w-a)}{(2a+w)} \tag{7}$$

Where: W = Specimen width

$2a$ = Crack length

V_c = Value of the clip gauge displacement

δ = Crack Opening Displacement (COD)

δ_c = Critical COD

3. <u>Fracture Mechanics Calculations</u> - <u>Crack Opening Displacement-Plane Strain Fracture Toughness Correlations</u>

The Critical Strain Energy release rate (G)[20] has been related with the COD by means of the following relationship:[21]

$$G_c = 2\ n\ \sigma_{YS}\ \delta_c \tag{8}$$

Where: G_c = Critical strain energy release rate

σ_{YS} = Yield strength at testing temperature

n = Factor to account the crack tip triaxiality and $1 \le n \le 1.5 - 2.0$

For Plane strain conditions: $n = 2$

and

$$G_c = \frac{K_{1C}^2}{E} (1 - \nu^2) \qquad (9)$$

Where: G_c = Critical strain energy release rate

K_{1C} = Plane strain fracture toughness

E = Young's modulus

ν = Poisson's ratio

In order to transform the COD values to K_{1C}, an empirical four point bend weldment test correction factor has been introduced. This factor, based on the experimental results, was found to be:

$$C = 38.10$$

Thus, equation (8) became:

$$G_c = 4C\, \sigma_{YS}\, \delta_c \qquad (10)$$

σ_{YS} at testing temperatures, when not available was obtained from the following equation:[22]

$$\sigma_{YS_T} = \sigma_{YS_{RT}} + (14500/(T + 459)) - 27.4 \qquad (11)$$

Where: σ_{YS_T} = Yield point at the desired temperature (Ksi)

$\sigma_{YS_{RT}}$ = Yield point at room temperature (Ksi)

T = Temperature of interest (°F)

D. EXPERIMENTAL FRACTURE TOUGHNESS VALUES MEASURED WITH THE DEEP NOTCHED BEND TEST

1. A-517 B Notched Specimens Test Results

A series of ASTM A-517 B, quenched and tempered high strength low alloy steel plates were tested with the deep notched specimen. The chemical composition of this steel is given in Table 1 and the Charpy impact test results in Table 3 and in Appendix 1. Crack opening displacement results are summarized in Table 5 and COD values vs. temperature curves obtained from the tests are plotted in Figure 12. K_{1C} values were determined for the specimens tested at lower temperatures using equation (6) (K_{1C} results are summarized in Table 6) and by means of equations (9) and (10), the COD values were calculated. The correction factor C = 38.10 was calculated by comparing equations (10) and (7), and using the experimental results of the specimen tested at -80°C. The dark points in Figure 12 correspond to COD determined from K_{1C} calculations.

With respect to fit of the data, it should be pointed out that for the specimen tested at -70°C the COD calculated from K_{1C} is closer to the average curve than the experimental COD. The reason for this difference was assumed to be due to the fact that the two COD values come from different experimental data. The calculated COD comes from K_{1C}, which is obtained using the applied load from a deflection-load recording. The experimental COD comes from the clip gauge readings. Thus one could speculate that there could be an experimental error on the COD recording during testing at -60°C.

Due to the fact that during the welding of the Hardex-N plug bead a heat affected zone is produced, the fracture toughness properties of the material surrounding the hard metal must be assumed to be affected. Therefore the crack tip position during testing is important, since the Four Point Bend Weldment Test is a crack initiation test, the fracture toughness of the material tested is that one at the tip of the crack. So, it was necessary that the crack in the Hardex-N stop not in the weld alone but extend to the material to be tested. Figure 13 shows a micrograph of the crack tip position for an A-517 B specimen bent under a low load to produce the full propagation of the crack in the hard metal. It can be seen in Figure 13 that the tip of the crack arrested in the material beyond the fine grained zone. Thus the weldment material, not the hard facing bead area is tested.

2. <u>A-537 Class 1 Submerged Arc Weldment Notched Specimens Test Results</u>

A second series of submerged arc welded specimens of A-537 Class 1 Steel, welded with high heat input (6 kJ/mm) were tested with the deeply notched specimen. The results for Four Point Bend Test are summarized in Table 7. Seven specimens were tested with the reinforcement removed and other three with the reinforcement intact. The specimens, as can be seen in Table 7, were notched in the base plate, HAZ and weld metal. For the weldments tested at -80°C there was crack propagation for the specimens notched in the base plate and HAZ. One of the specimens notched in the HAZ was tested with the reinforcement removed and the other one with the reinforcement intact. COD results for these specimens are not significantly different. For the specimens notched in the weld metal there was crack extension only for those tested to and under -100°C. COD values vs. temperature for the base plate and HAZ notched specimens are plotted in Figure 14. Figure 14 also shows data obtained from reference (7) for A-537 Class 1 steel electroslag welded and tested in the as-welded condition. Table 8 shows plane strain fracture toughness results obtained from reference (7) and transformed by means of equations (9) and (10) to COD K_{1C} values in reference (7) were obtained from ASTM E-399 70T plane strain fracture toughness compact tension specimens. Comparison of the K_{1C} and COD values for base metal and HAZ from the current experiments and the literature shows that they are in good agreement, which suggests that the results obtained by means of the four point bend test are reasonable.

Figure 15 shows three specimens tested with the notch in the base plate, HAZ and weld metal. It can be seen from this figure that for the three different notch positions, the crack has propagated within the material to be tested, and that the propagation is parallel to the notch (i.e. remains in the region of interest).

Analysis of the above results, obtained from testing the four point bend test specimens with the deep notch has revealed that:

(a) The crack runs always perpendicular to the longitudinal stresses and parallel to the notch (Figure 16).

(b) Even if several cracks appear in the Hardex-N plug bead (especially after grinding) there is always a crack that goes from the end of the notch through the hard metal, parallel to the notch, and is this one which propagates during testing (Figure 17).

(c) As can be seen in Figure 18, the assumed semi-elliptical notch for fracture toughness calculations fits well with the experimental one.

(d) The test has appeared easy to control and the instrumentation and experimental procedure simple.

CONCLUSIONS

The results of this study into the development of a fracture toughness weldment test indicate that:

(1) The initially developed four point bend test specimen with a Hardex-N crack starter bead does not allow plane strain fracture toughness calculations at practical temperatures because of the high applied bending load which leads to general yielding in the specimen in most cases.

(2) The position of the natural cracks produced in the crack-starter are not able to be controlled. The hardex-N weld bead breaks non-uniformly and the crack size is small, which leads to high load to fracture.

(3) The combination mechanical notch-Hardex-N plug weld allows the possibility of putting a natural crack in any place of the weldment and to have the crack tip in the right position.

(4) The calculated COD and K_{1C} from the data obtained from the four point bend test notched specimens appears to have a reasonable accuracy.

(5) The four point bend test can be used as a comparison test between steels or as a specific test by utilizing fracture toughness calculations from the results.

TABLE 1

Chemical Composition of the Steels Tested

ASTM Specification	C	Mn	P	S	Si	Ni	Cr	Mo	V	Ti	Cu	Al	B
A-537 Class 1	.17	1.22	.008	.014	.24	.15	.22	.027	.003	.006	.14	.035	
A-517-B	.16	.87	.005	.017	.26	.03	.50	.16	.038	.006			.003

Typical Chemical Composition of the Welding Wire

Specification	C	Mn	P	S	Si	Ni	Cr	Mo	Cu
ARMCO W-19	.10	.80	.01	.008	.09	3.45	.15	.08	.15(1)

(1) excluding coating

TABLE 2

Results of Four Point Bend Tests on A-537 Class 1 Steel
(from reference 9)

Temperature (°C)	Load (Kn)	Deflection (mm)	Specimen Orientation	Failure Location from Centerline (mm)	Notes
-40	263	76	transverse	38	1
-40	271	76	longitudinal	no break	
-50	240	54	transverse	38	
-50	223	56	longitudinal	19	
-60	212	30	longitudinal	13	
-70	208	24	longitudinal	0	
-80	245	23	longitudinal	5	
-94	239	12	longitudinal	0	

1. Pop-in only - 51 mm long

TABLE 3

Conventional Charpy V-Notch Transition Temperatures

Material	Condition	Position	Criteria	Temperature (°C)
A-537 Cl. 1	Unwelded	-	20 J	-40
			41J	-30
			.381 mm	-29
			50% FF	-15
	Submerged arc welded HI = 6 kJ/mm	H.A.Z.	20 J	-51
			41 J	-40
			.381 mm	-36
			50% FF	-24
		W.M.	20 J	-45
			41 J	-18
			.381 mm	-19
			50% FF	-8
	Submerged arc welded	Base Plate	20 J	-43
			41 J	-34
			.381 mm	-32
			50% FF	-18
		W.M.	20 J	-91
			41 J	-15
			.381 mm	-65
			50% FF	-68
A-517 B	Unwelded	-	41 J	-68
			.762 mm	-53
			50% FF	-31

TABLE 4

Results of Four Point Bend Tests on A 537 Class 1 Steel Weldments

Temperature (°C)	Load (KN)	Deflection (mm)	Failure Location	Failure Location from Center Line (mm)
Low Heat Input Weld - Reinforcement Intact				
-20	276	89	no break	no break
-30	284	84	base plate	20
-40	276	71	base plate	35
Low Heat Input Weld - Reinforcement Removed				
-20	274	76	no break	no break
-30	252	48	base plate	20
-40	258	51	base plate	22
High Heat Input Weld - Reinforcement Intact				
-30	290	64	no break	no break
-40	279	43	base plate	-
-50	236	30	base plate	28
High Heat Input Weld - Reinforcement Removed				
-20	287	76	no break	no break
-30	285	76	base plate	25
-40	290	56	base plate	18

TABLE 5

Results of Four Point Bend Test on A-517 B

Specimen Notched

Temperature (°C)	Load KN	Crack Length (2a) (mm)	Crack Depth (mm)	δ (mm)
-20	412	86.995	8.890	0.4583
-40	400	85.674	8.890	0.3457
-50	401	86.868	8.890	0.2971
-60	378	84.785	8.890	0.1757
-70	391	78.689	8.890	0.2664
-80	391	86.995	8.890	0.2566

TABLE 6

Results of Four Point Bend Test on A-517 B

Specimen Notched

Temperature (°C)	K_{1C} MPa$\sqrt{m}$	G MPa m	YS MPa	$\delta_{(calculated)}$ (mm)
-20	-	-	-	-
-40	-	-	-	-
-50	-	-	-	-
-60	84.43	31.50	858.15	0.24
-70	89.45	35.36	871.05	0.27
-80	87.36	33.76	885.25	0.25

TABLE 7

Results of Four Point Bend Test on A-537 Class 1 Steel Weldments

Series High Heat Input - Specimen Notched

	Slotte Location	Temperature (°C)	Load (K_N)	Deflection (mm)	Crack Length(2a) (mm)	Crack Depth (mm)	δ_c (mm)
Reinforcement removed	B.P.	-40	187	9.65	85.17	8.89	0.222
	H.A.Z.	-40	231	25.40*	83.44	8.89	-
	H.A.Z.	-60	227	25.40*	88.65	8.89	-
	H.A.Z.	-80	197	-	81.53	8.89	0.1040
	W.M.	-40	231	25.40*	81.92	8.89	-
	W.M.	-100	255	-	71.12	8.89	0.1683
	W.M.	-135	138	-	88.90	8.89	0.0480
Reinforcement intact	B.P.	-80	187	10.67	86.31	8.89	0.124
	H.A.Z.	-80	200	10.16	79.63	8.89	0.117
	W.M.	-80	249	25.40*	77.72	8.89	-

* loads are reported for 25.4 mm deflection, which is the maximum deflection allowed by the equipment.

TABLE 8

Fracture Toughness Results on ASTM A-537 Grade A Steel Weldments

Tested in the As-welded Condition (from reference 7)

Material Tested	Testing Temperature (°C)	K_{1C} (MPa$\sqrt{m}$)	Yield Strength .2% offset (MPa)	G (MPa·m)	δ_c (mm)
Base Plate	-73	52.95	381.29	12.39	0.21
	-87	44.18	402.74	8.63	0.14
	-101	45.39	424.04	9.11	0.14
	-157	30.81	593.66	4.19	0.05
Heat affected zone	-68	59.31	374.40	15.55	0.27
	-82	45.83	394.05	9.28	0.15
	-87	46.59	402.74	9.60	0.16
	-101	42.65	424.04	8.04	0.12
	-129	39.47	502.65	6.88	0.09

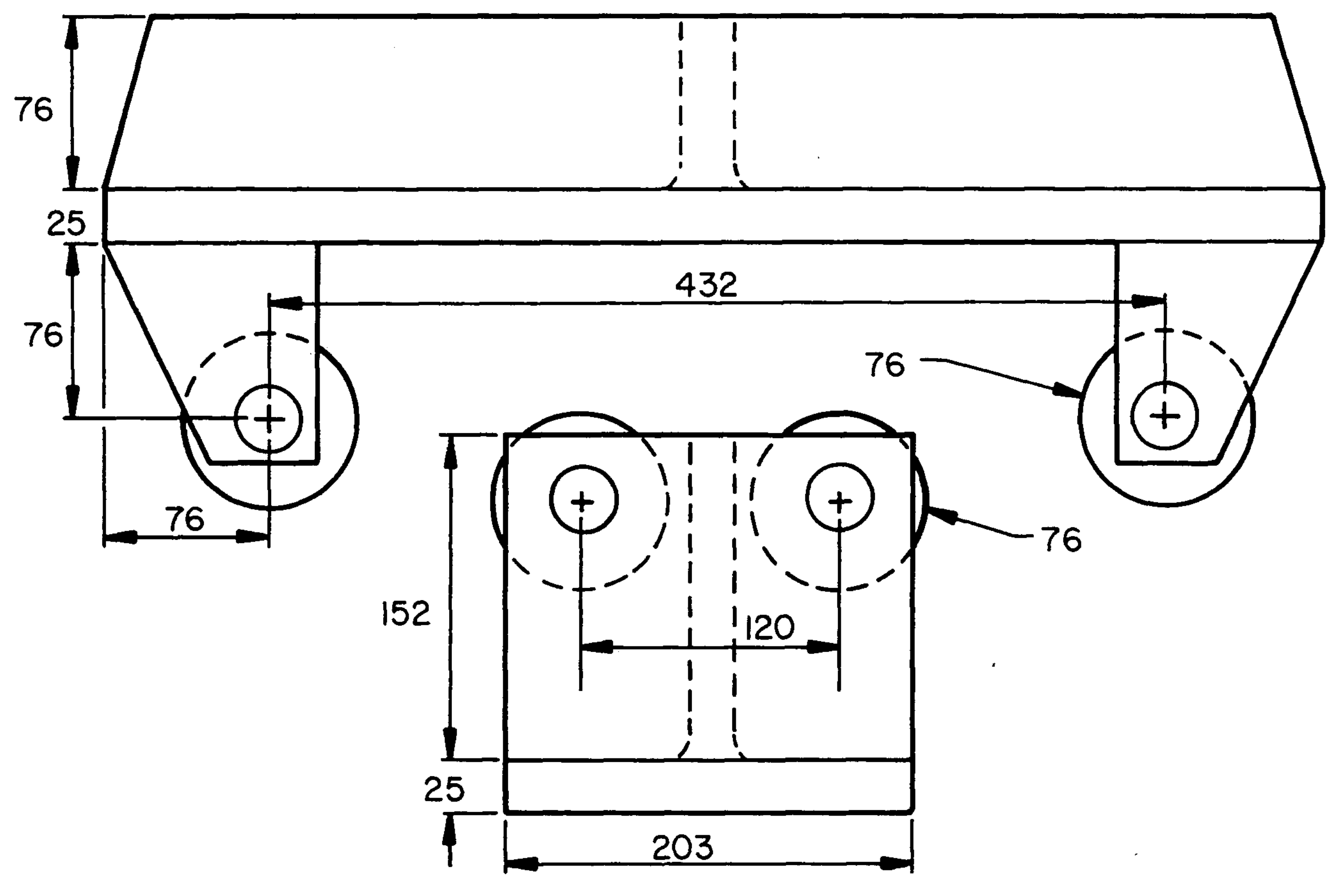
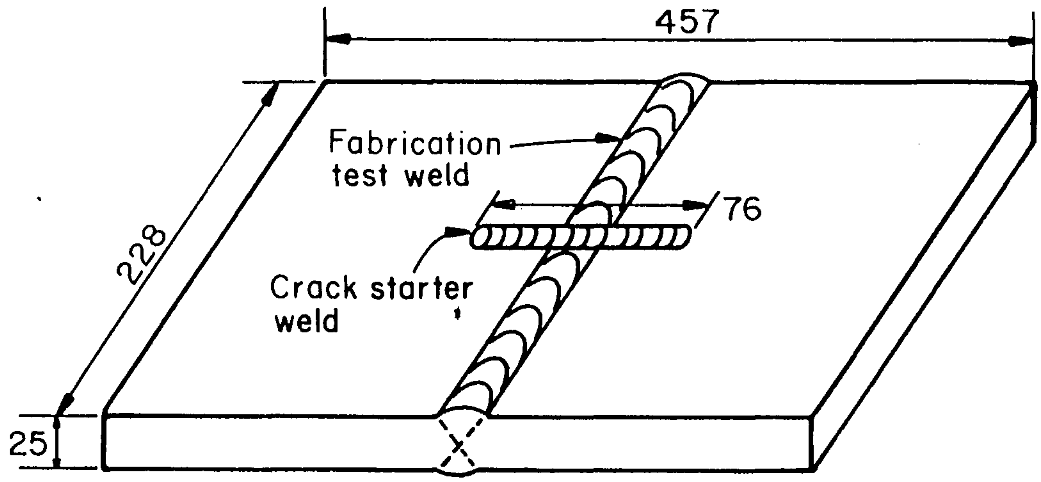


Fig. I - Four Point Bending Jig (From reference 9)



a. Schematic diagram of four point bend test plate.

b. ASTM A-537 Class I Submerged arc welded,
Heat input: 2 kJ/mm, as welded
Crack starter bead: Hardex-N

Fig.2 - Four point bend test original specimen

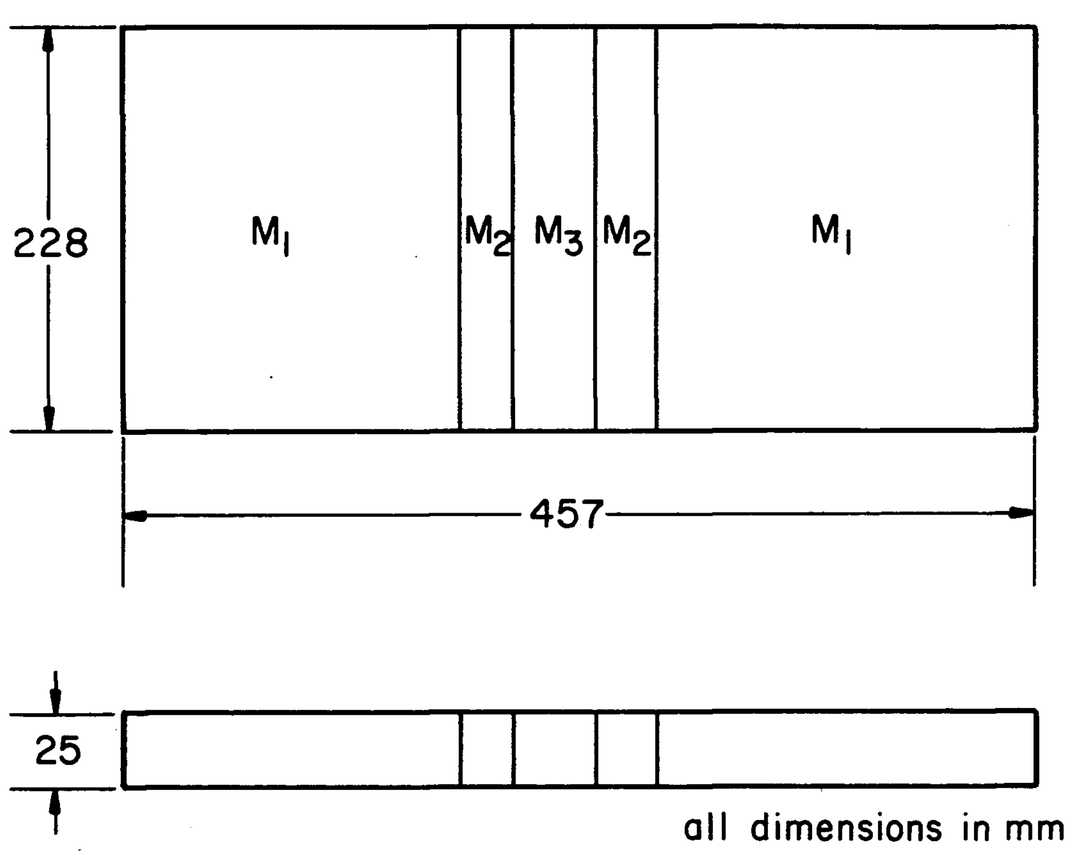


Fig. 3 - Idealized Composite Material

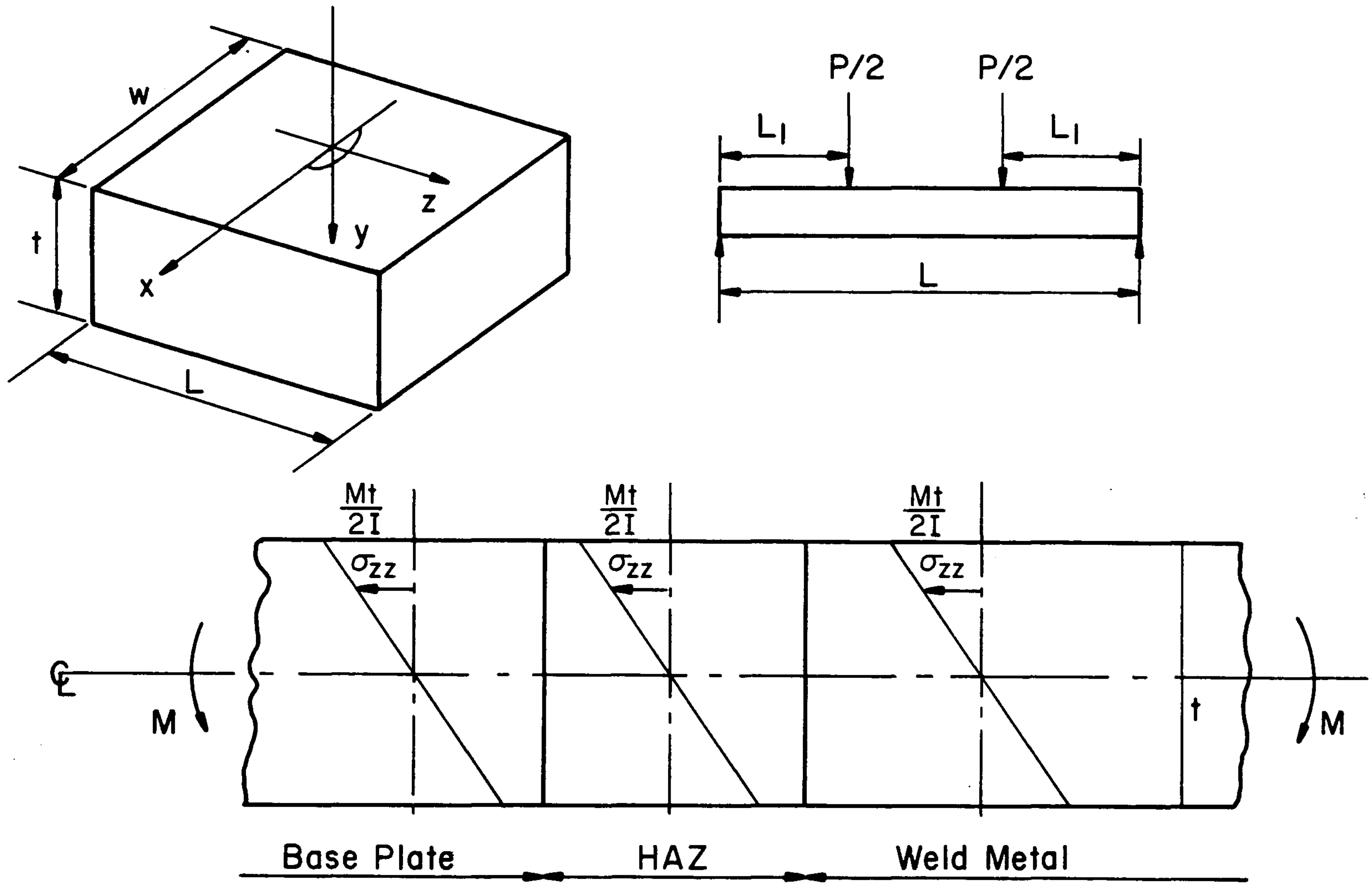


Fig. 4 – Elastic bending of a weldment-plate

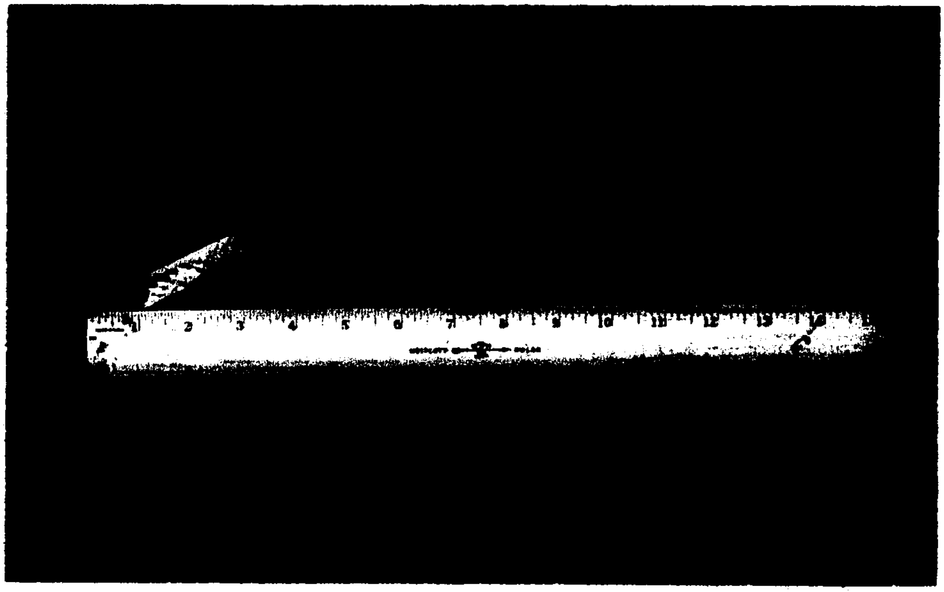


Fig.5a. As welded, reinforcement intact, deflection=68mm.

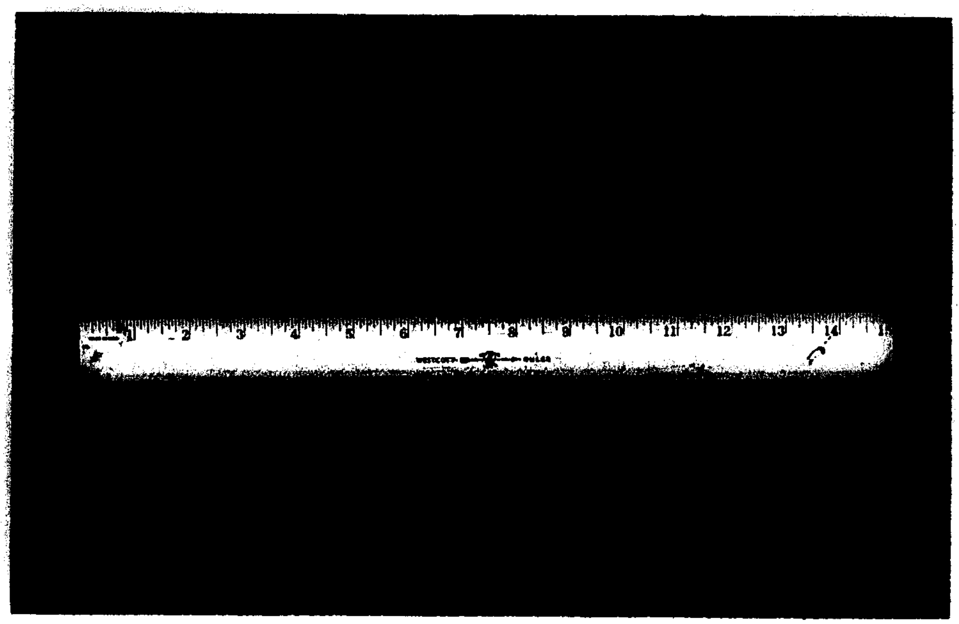


Fig.5b. Reinforcement removed, deflection=97mm.

Fig.5 ASTM A537 Cl.I. Submerged arc weld. Heat input = 2 kJ/mm. Temperature = -20 C, Load = 275 kN, as welded.

Fig.6a. As welded, testing temperature = -50°C, deflection = 31 mm.

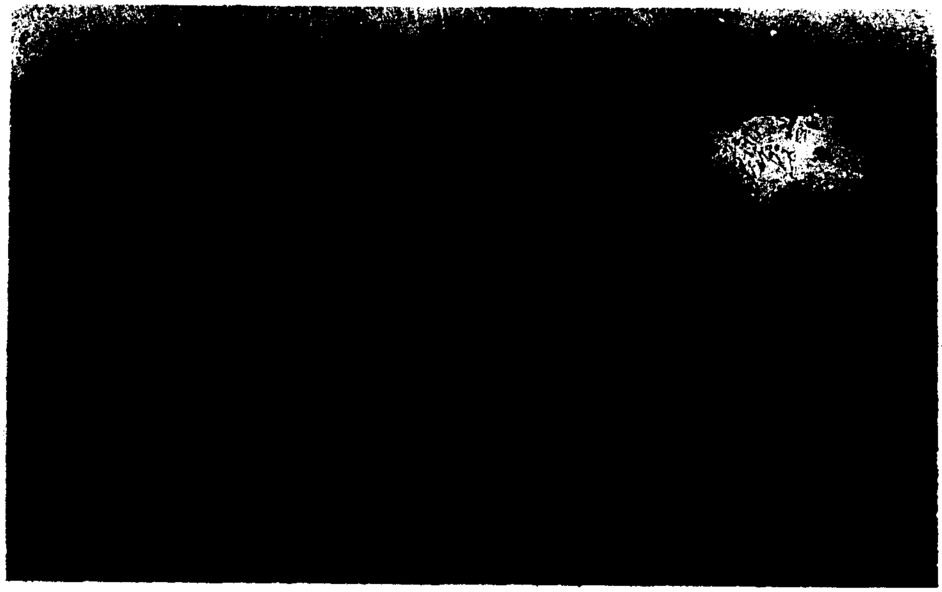


Fig.6b. As welded, testing temperature = -40°C, deflection = 43 mm.

Fig. 6. ASTM A537 Cl. I, Submerged arc weld, Heat Input = 6 kJ/mm. Four point bend test specimen.

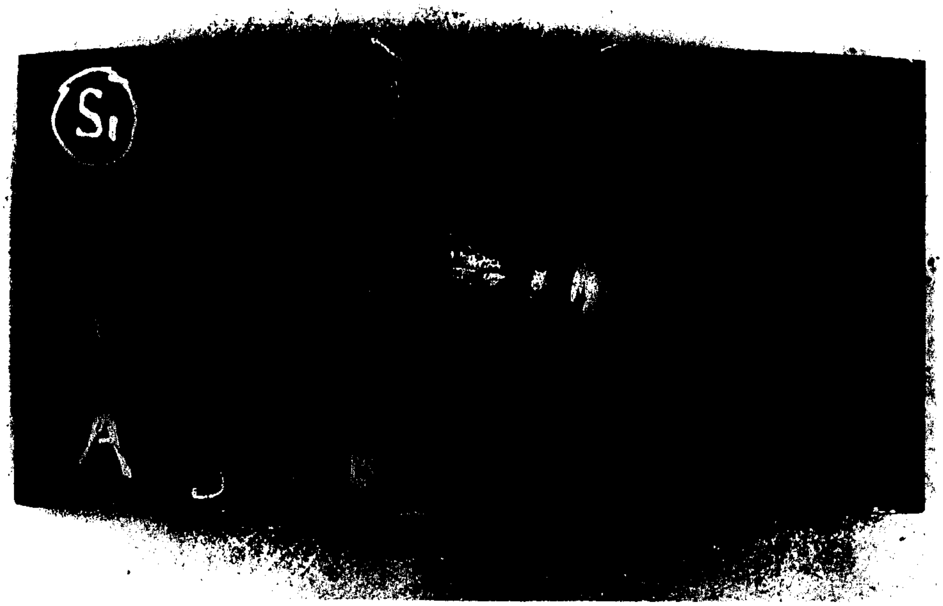


Fig.7a. Extended size starter weld beads: left-60mm, right-20mm. Starter bead notched.

Fig.7b. Extended size starter weld bead: 40mm wide, notched. Failure initiates in unnotched region.

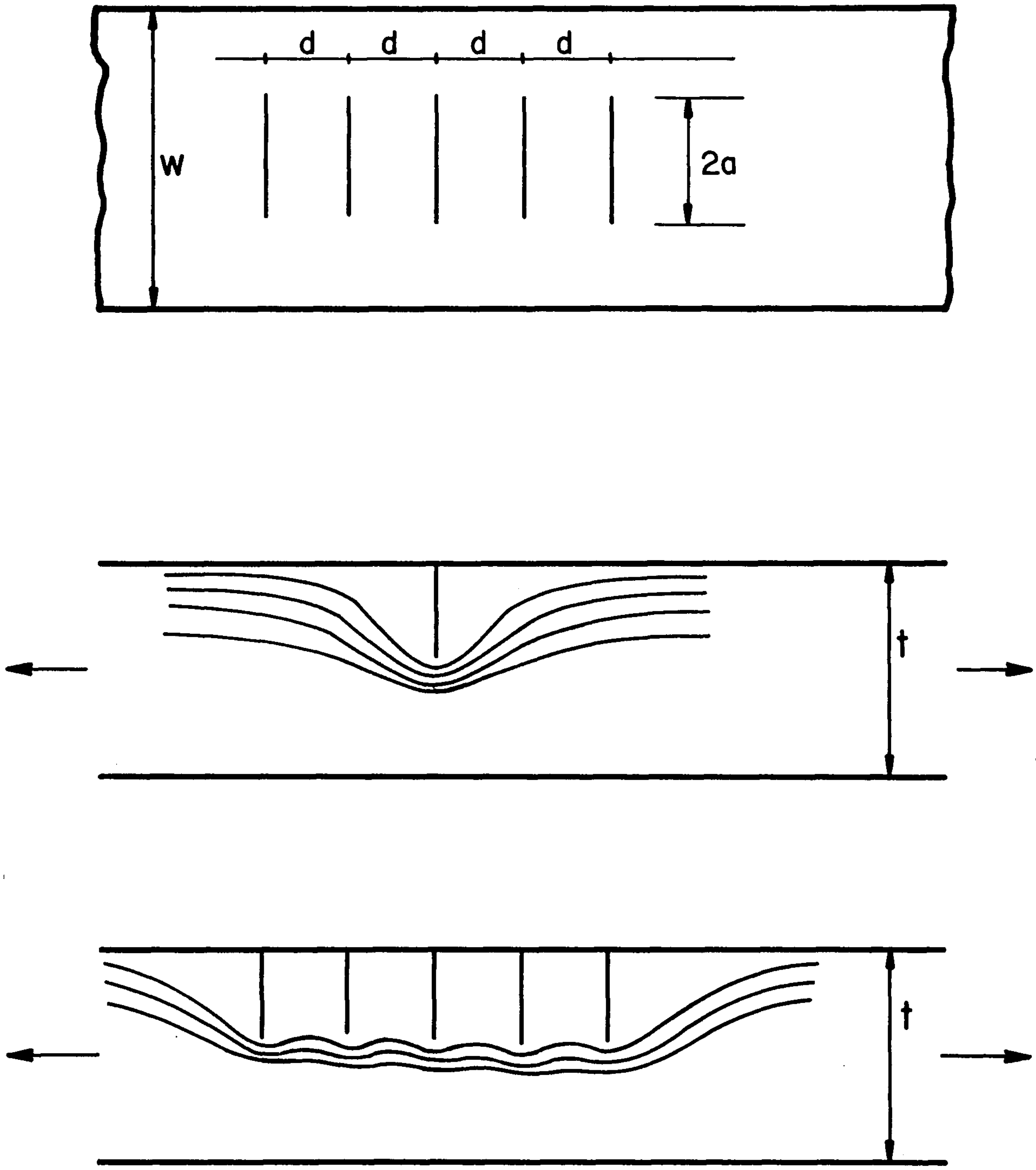


Fig.8 - Schematic view of the effect of several cracks in a plate. (18)

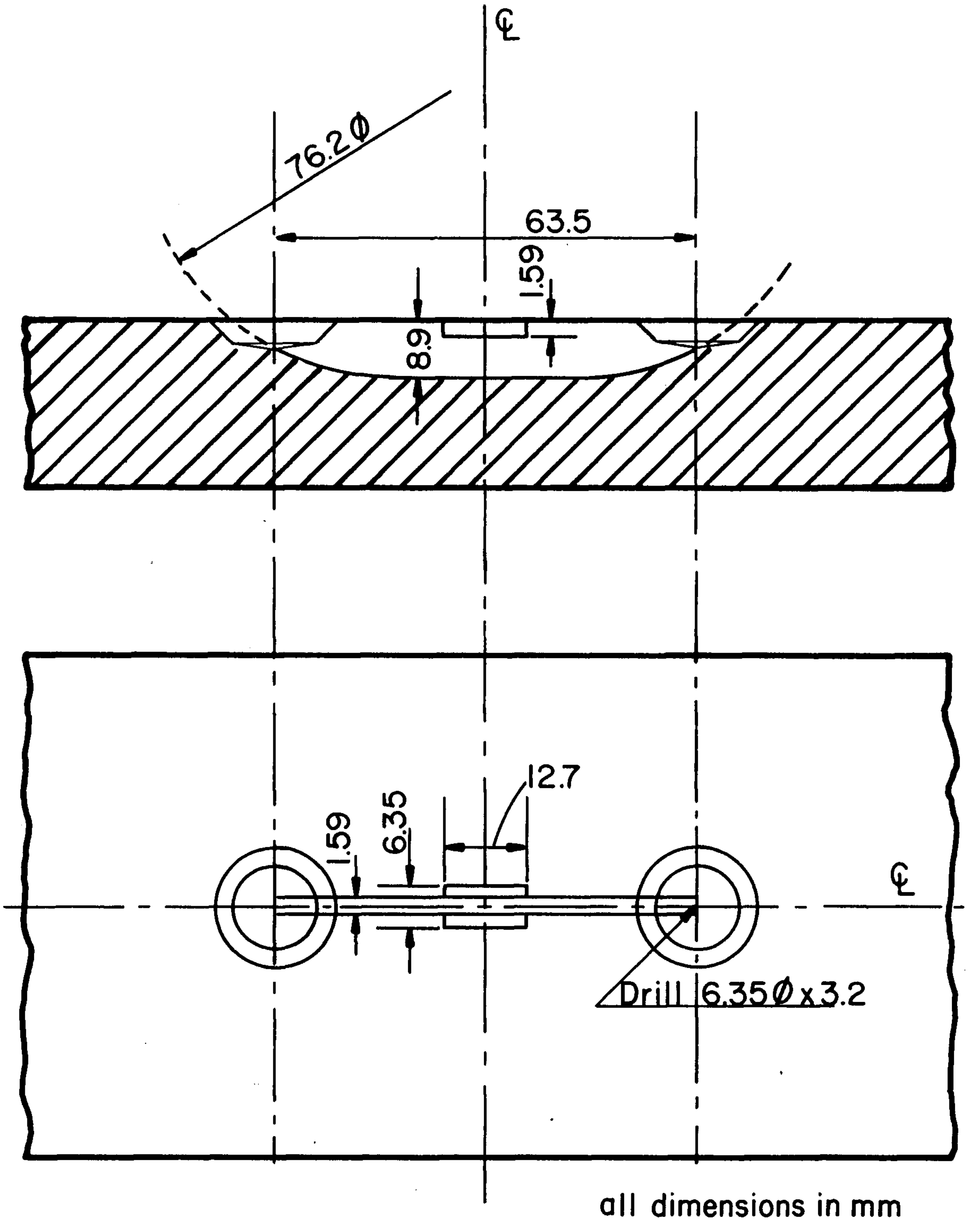


Fig. 9 - Four point bend test specimen - notch design.

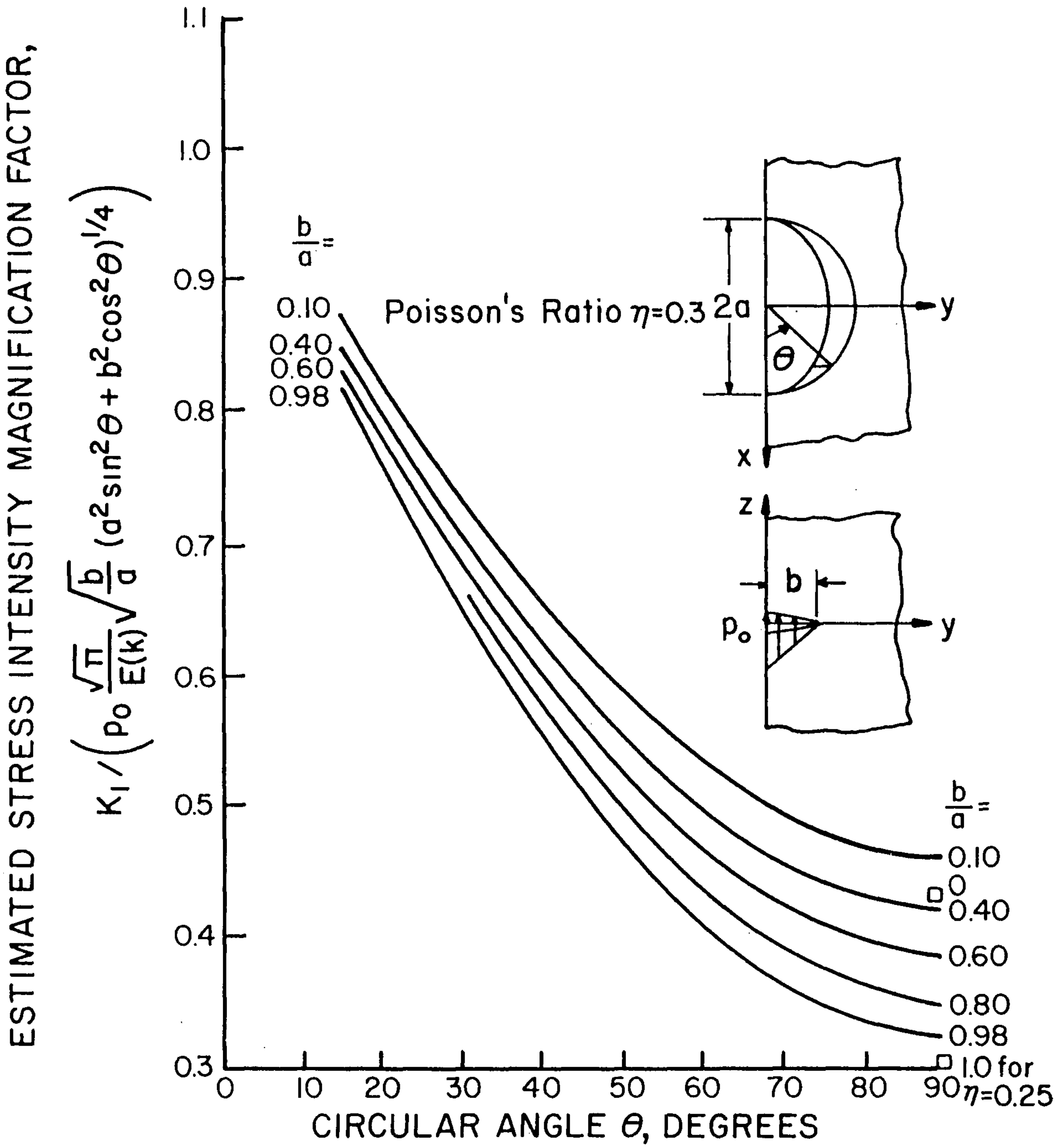


Fig.(10) - Estimated stress intensity factor of a semi-elliptical flaw in a half space subjected to a linearly varying load. (From reference 14)

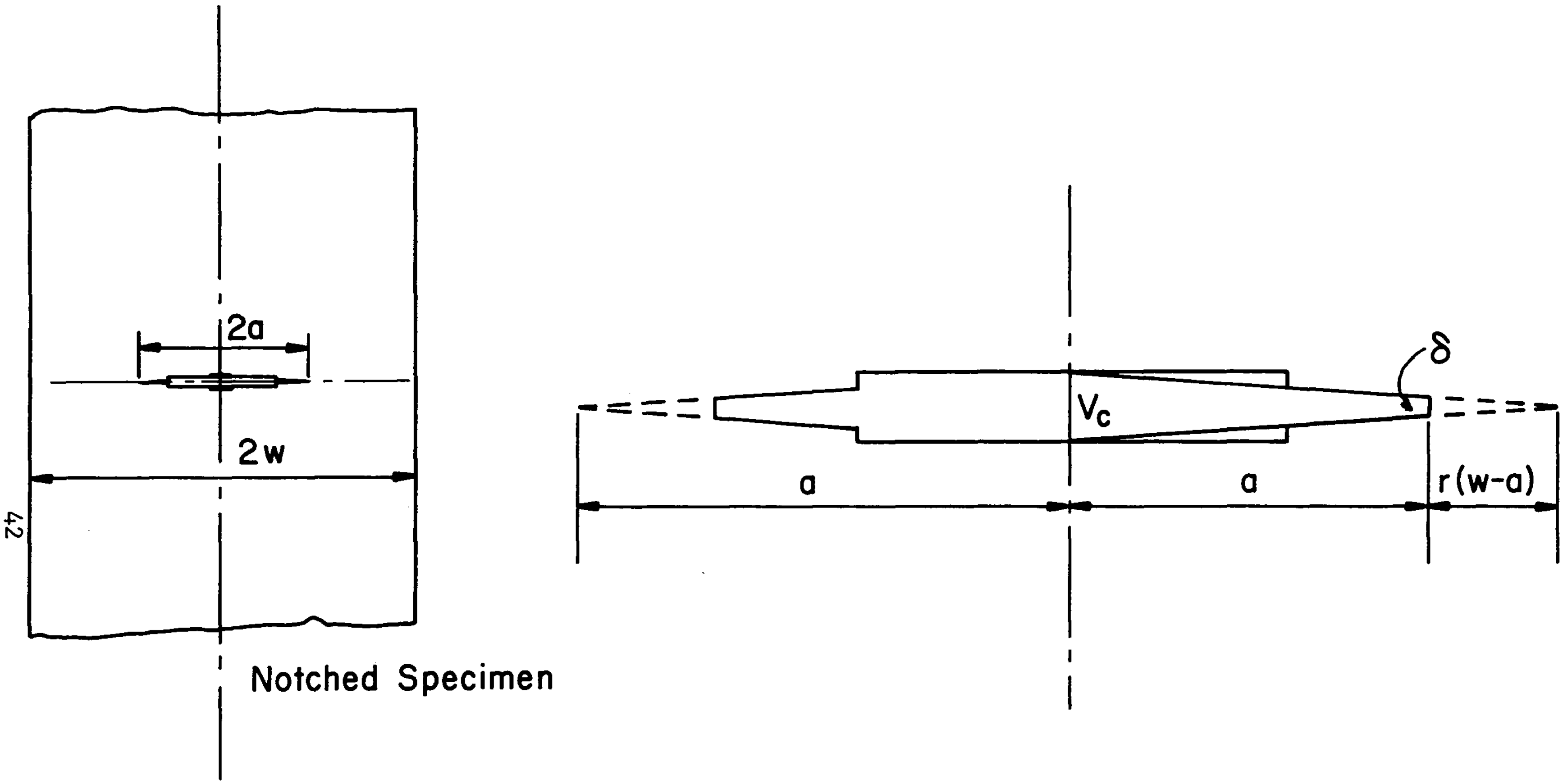


Fig.11 - Representation of the notch profile during bending

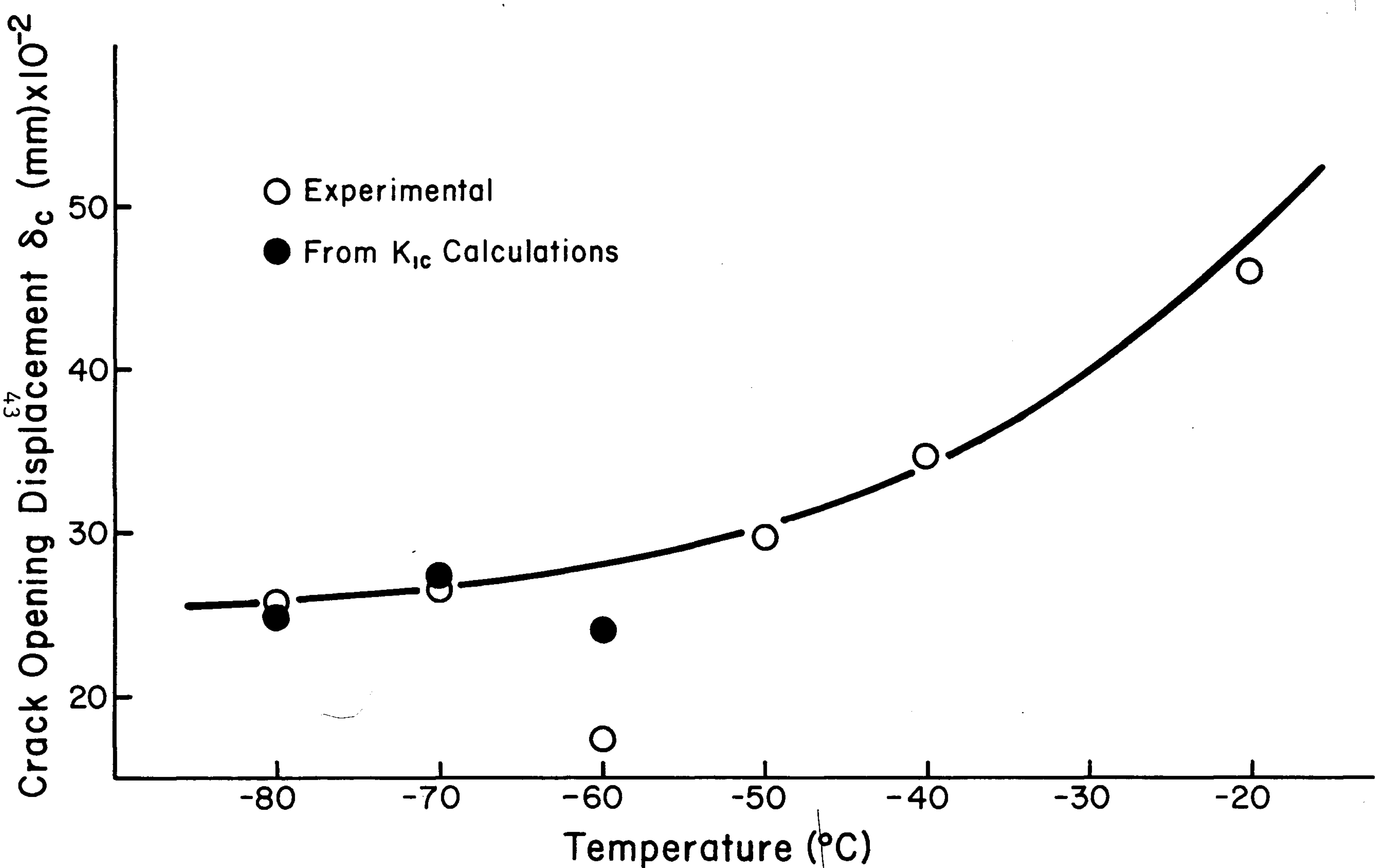


Fig.12-ASTM A-517B Steel weldments - Four point bend test results

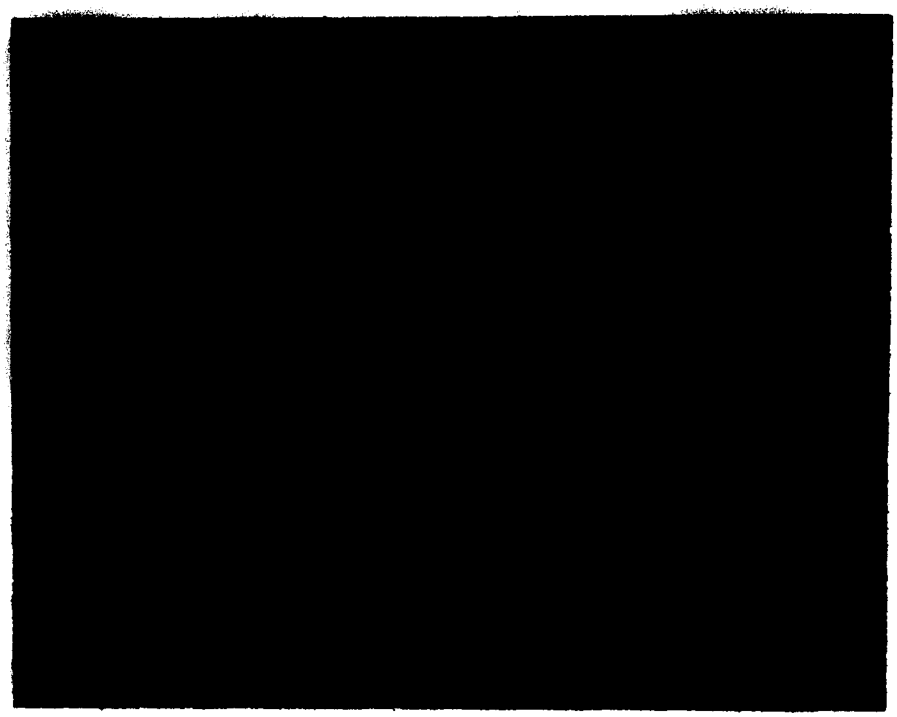


Fig.13 A-517B Steel-Four point bend specimen.
Crack tip position before testing.
Nital 2% x50

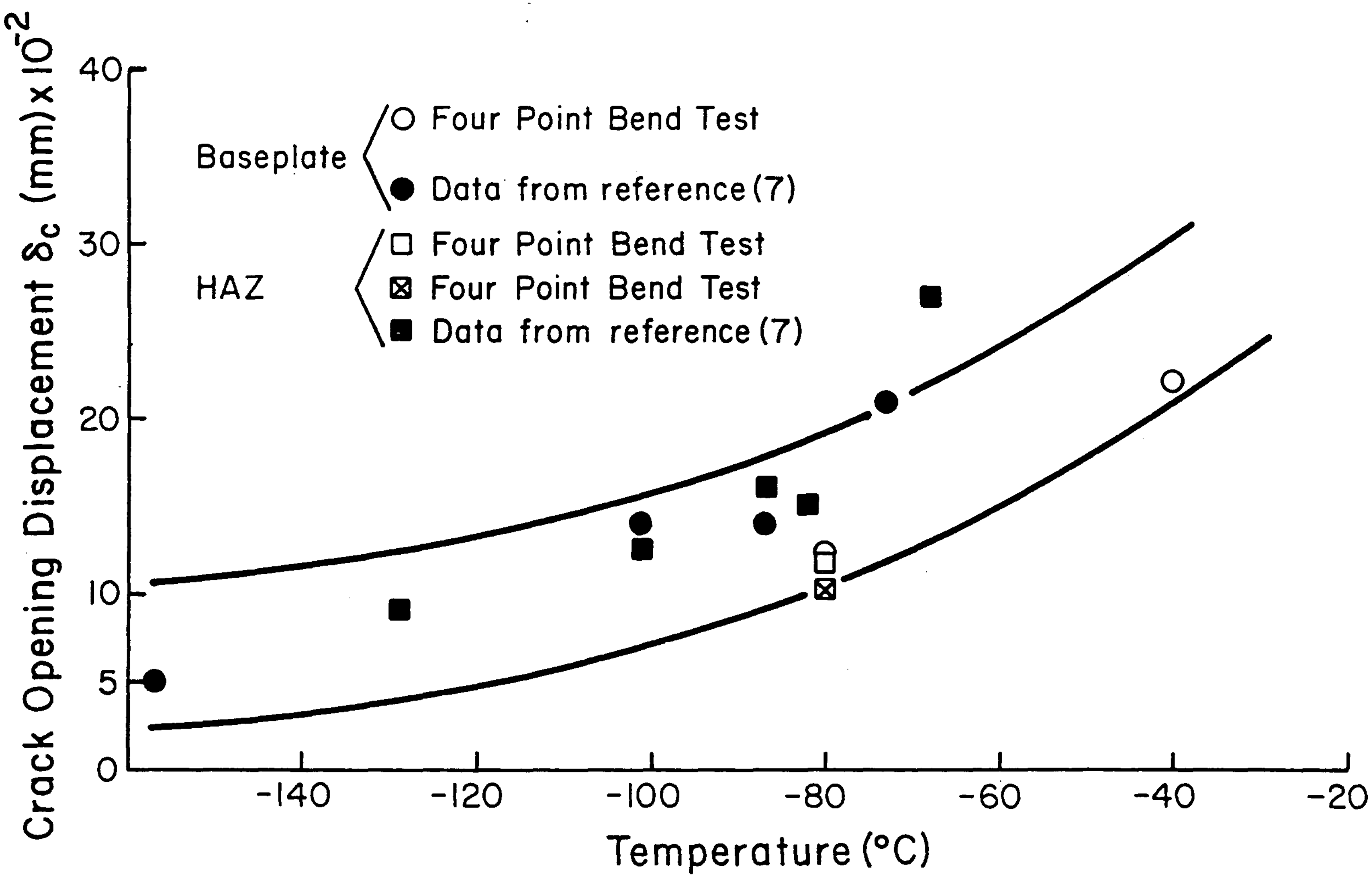


Fig.14 - ASTM A-537 Class I Steel weldments - Four point bend test results

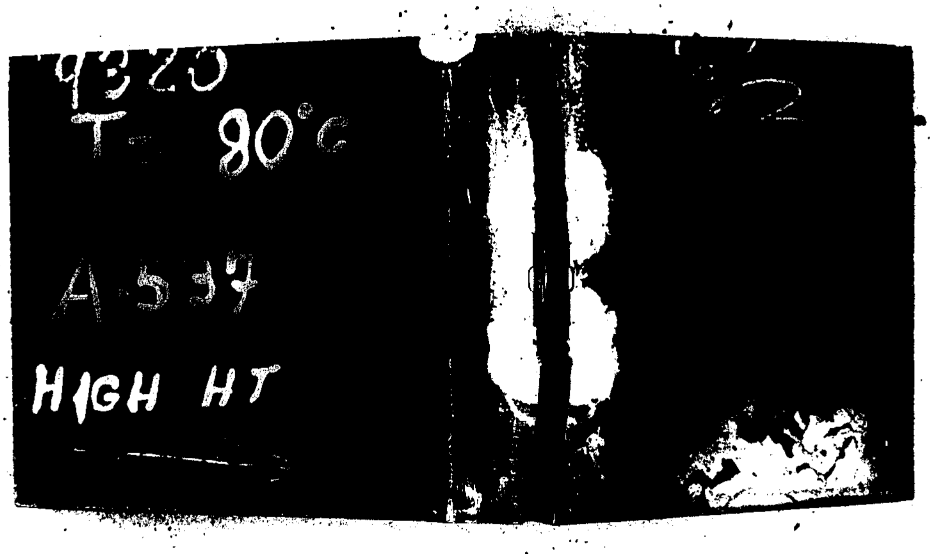


Fig. 15a. Specimen notched in the base plate.

Fig. 15b. Specimen notched in the HAZ.

Fig.15c. Specimen notched in the weld metal.

Fig.15 ASTM A537 Cl. I. Submerged arc weld, Heat input = 6 kJ/mm. Specimens with different notch positions.

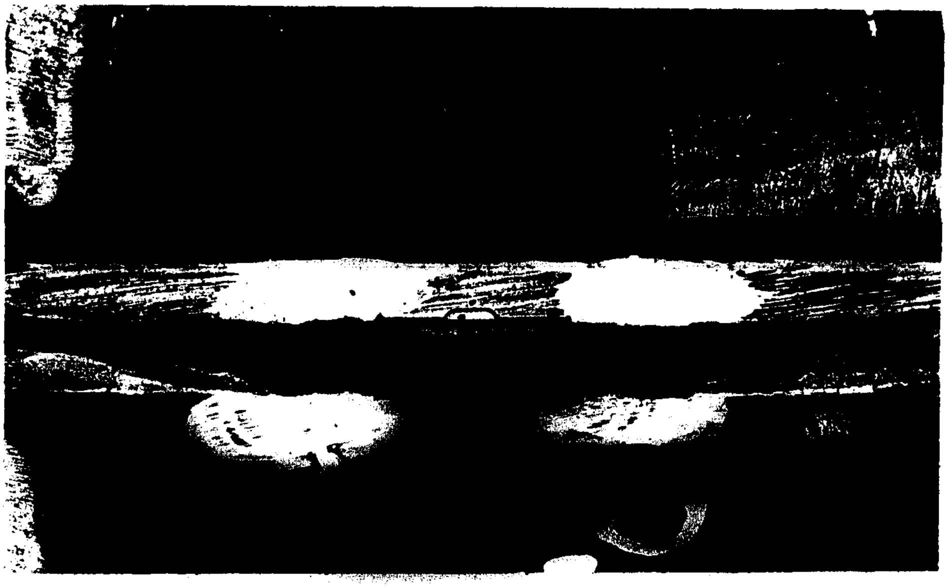


Fig. 16 Four point bend test notched specimen showing the fracture pattern.

Fig. 17 Four point bend test notched specimen showing the crack propagated parallel to the notch.

Fig.18 Fracture surface of a four point bend test specimen showing the semi-elliptical shape of the notch.

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APPENDIX 1

Conventional Charpy V-Notch Transition Curves for

for Base Plates, Heat Affected Zone and Weld Metal.

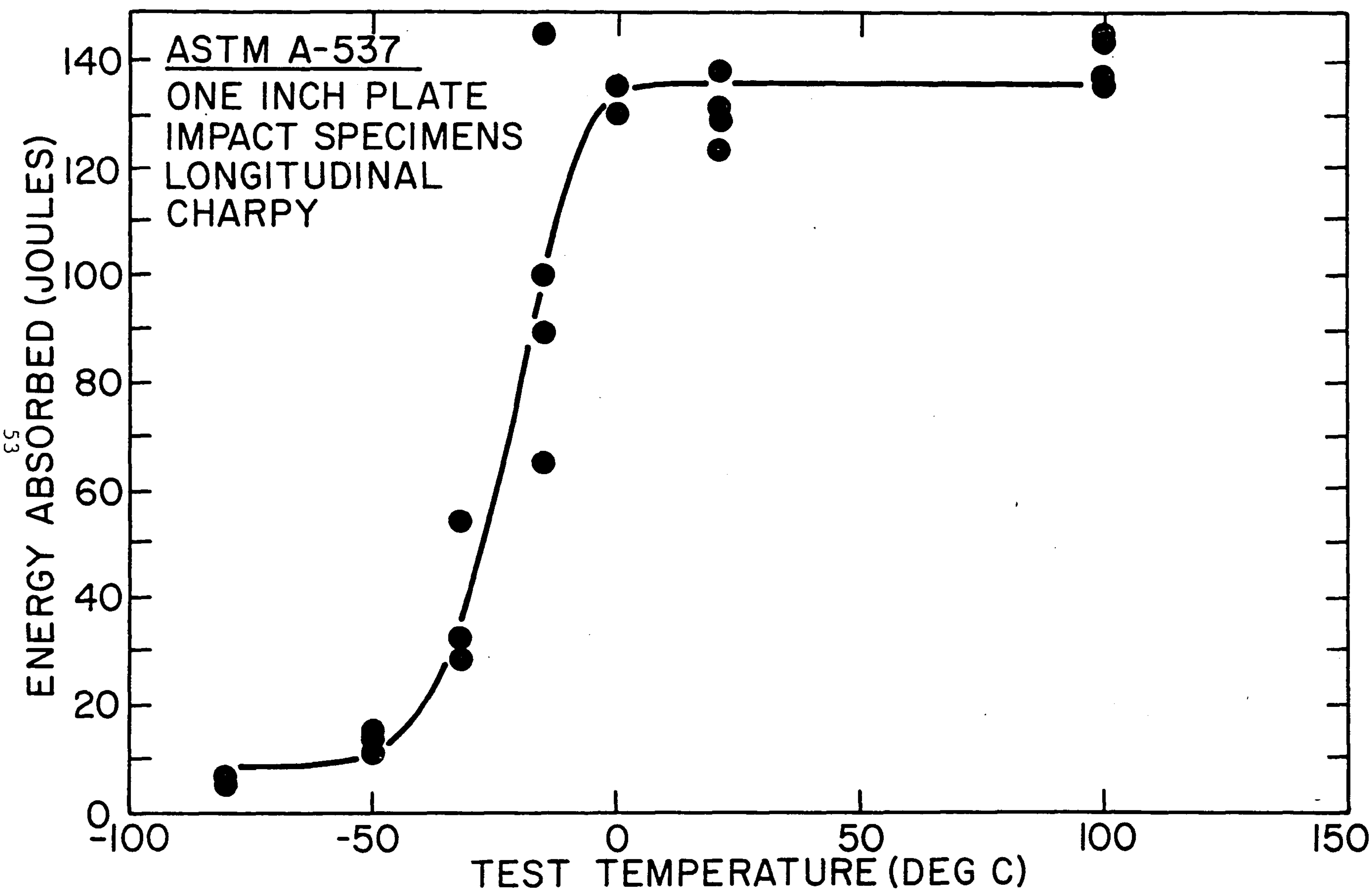
ASTM A-537
ONE INCH PLATE
IMPACT SPECIMENS
LONGITUDINAL
CHARPY
ENERGY ABSORBED (JOULES)
0
20
40
60
80
100
120
140
-100
-50
0
50
100
150
TEST TEMPERATURE (DEG C)

FIGURE 1a.

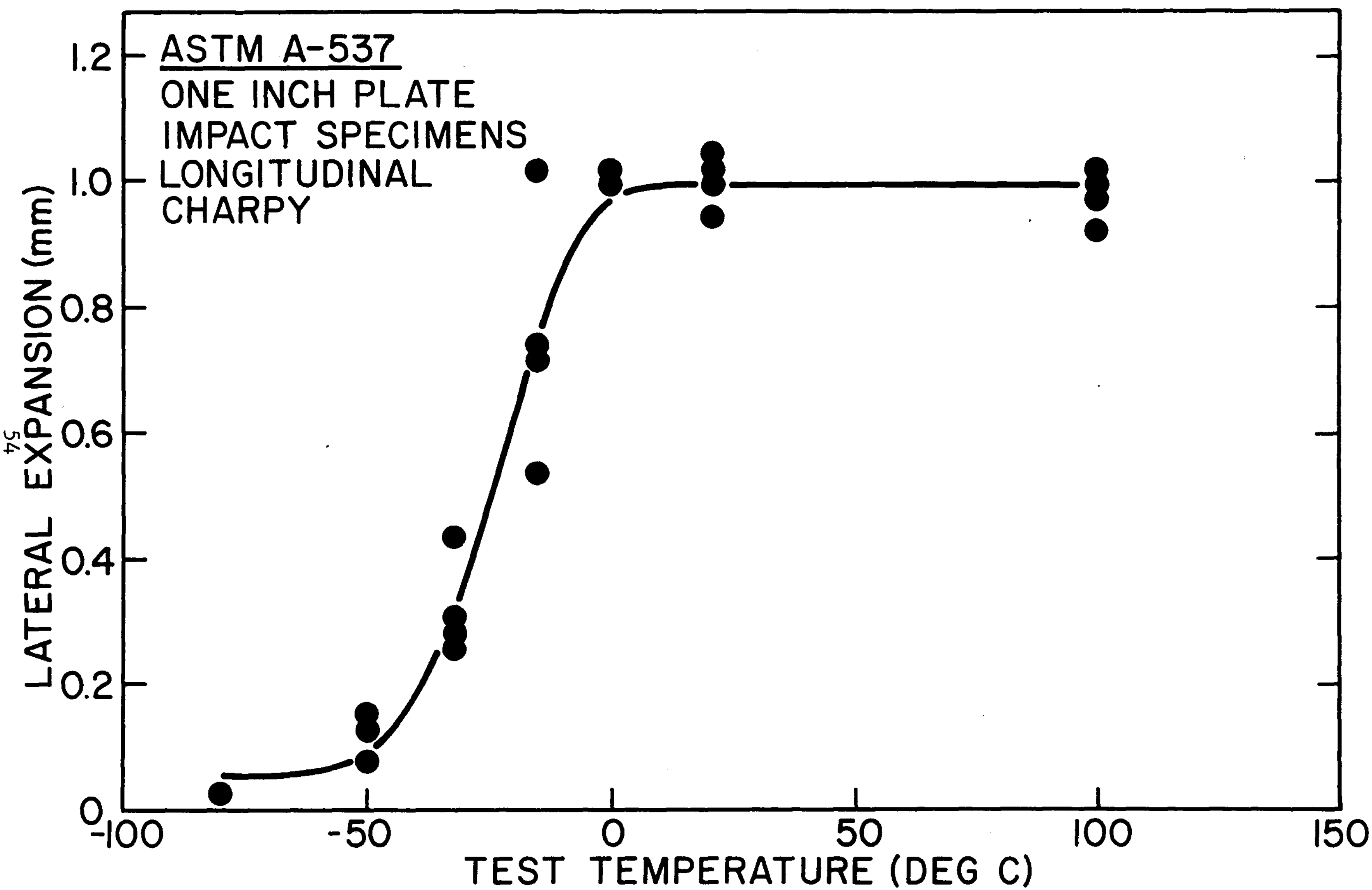
ASTM A-537
ONE INCH PLATE
IMPACT SPECIMENS
LONGITUDINAL
CHARPY
LATERAL EXPANSION (mm)
0
0.2
0.4
0.6
0.8
1.0
1.2
-100
-50
0
50
100
150
TEST TEMPERATURE (DEG C)

FIGURE 1b.

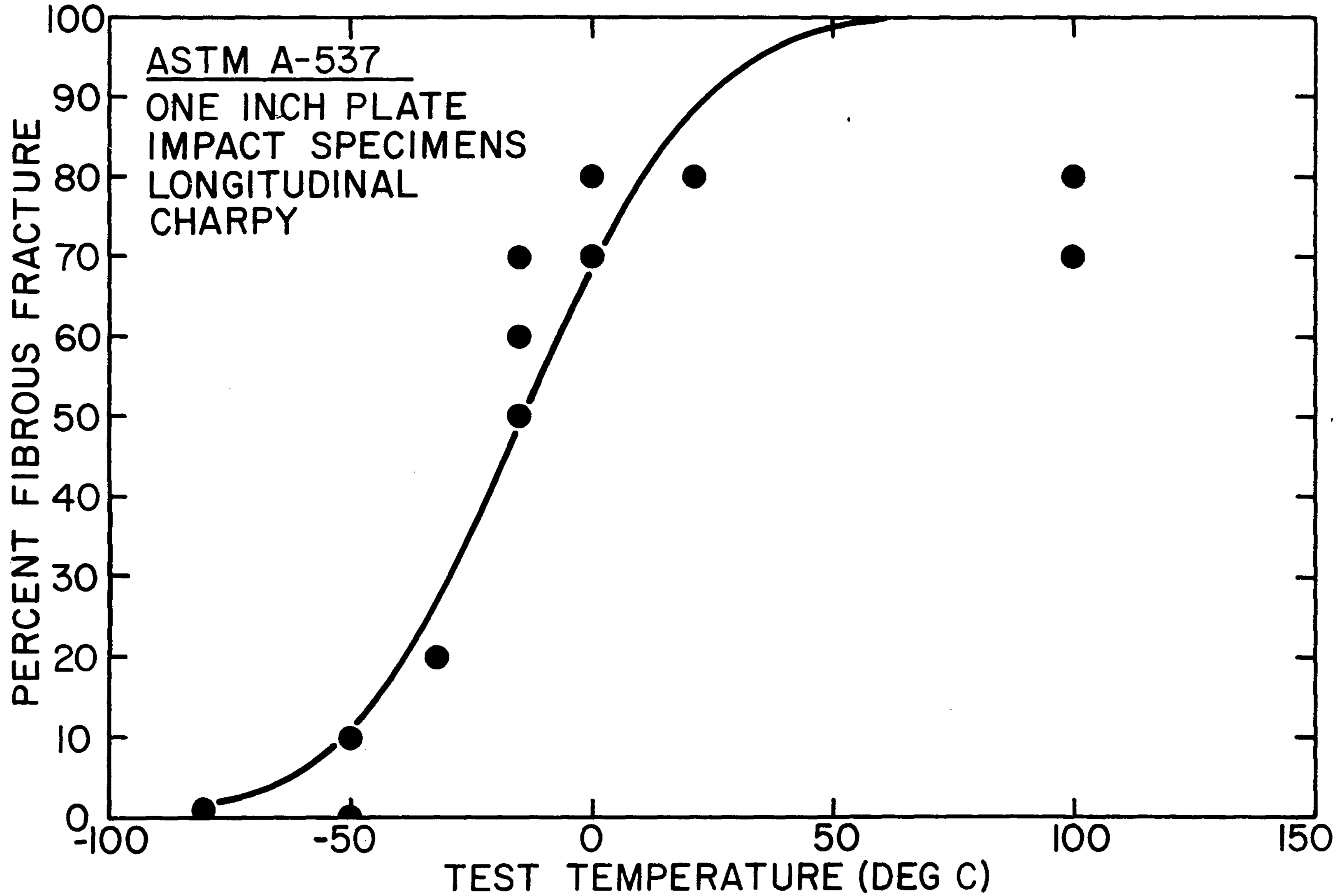
ASTM A-537
ONE INCH PLATE
IMPACT SPECIMENS
LONGITUDINAL
CHARPY
PERCENT FIBROUS FRACTURE
100
90
80
70
60
50
40
30
20
10
0
-100
-50
0
50
100
150
TEST TEMPERATURE (DEG C)

FIGURE Ic.

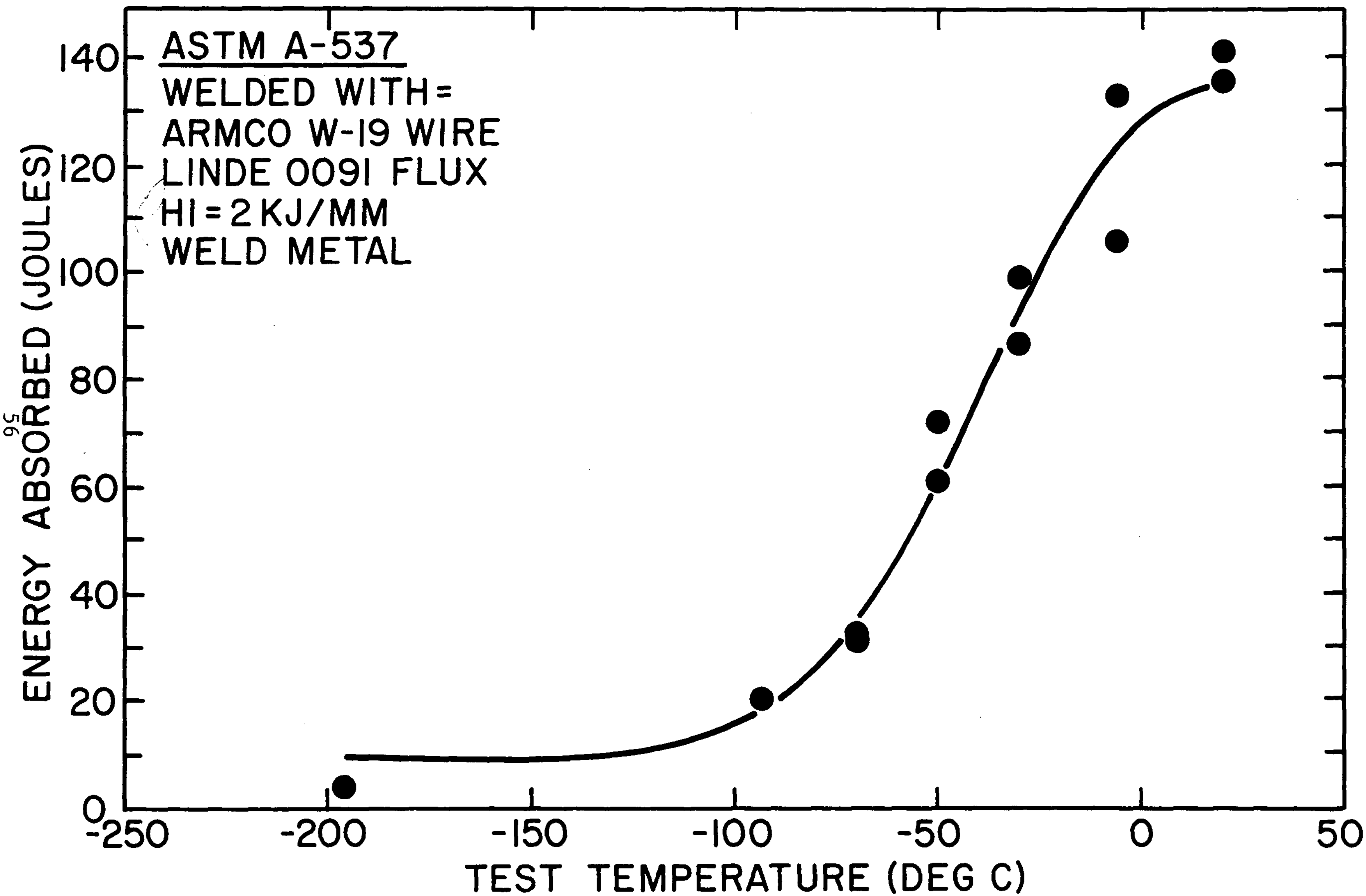
ASTM A-537
WELDED WITH=
ARMCO W-19 WIRE
LINDE 0091 FLUX
HI=2 KJ/MM
WELD METAL
ENERGY ABSORBED (JOULES)
0
20
40
60
80
100
120
140
-250
-200
-150
-100
-50
0
50
TEST TEMPERATURE (DEG C)

FIGURE 2a.

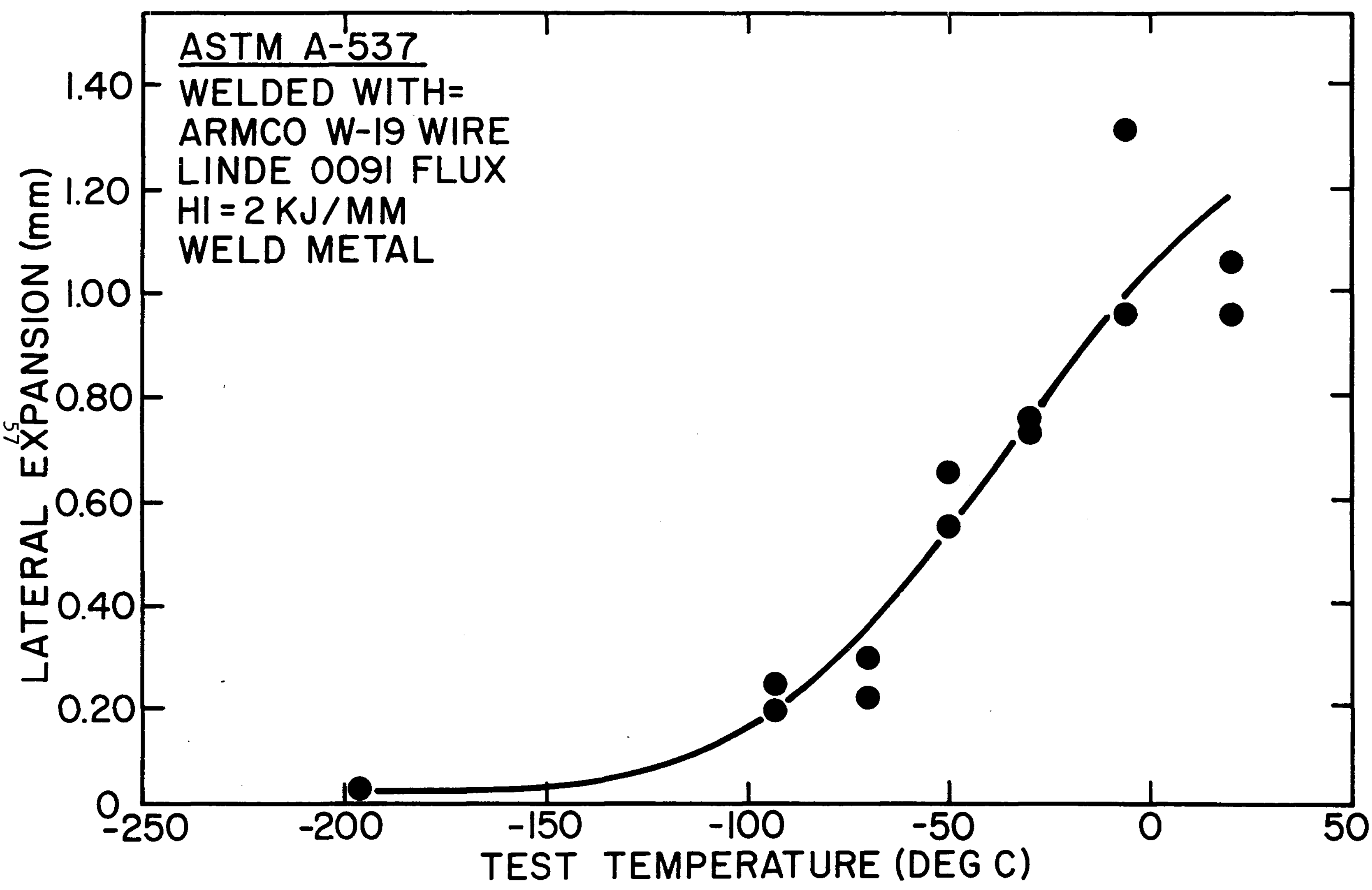
ASTM A-537
WELDED WITH=
ARMCO W-19 WIRE
LINDE 0091 FLUX
HI = 2 KJ/MM
WELD METAL
LATERAL EXPANSION (mm)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0
-250
-200
-150
-100
-50
0
50
TEST TEMPERATURE (DEG C)

FIGURE 2b.

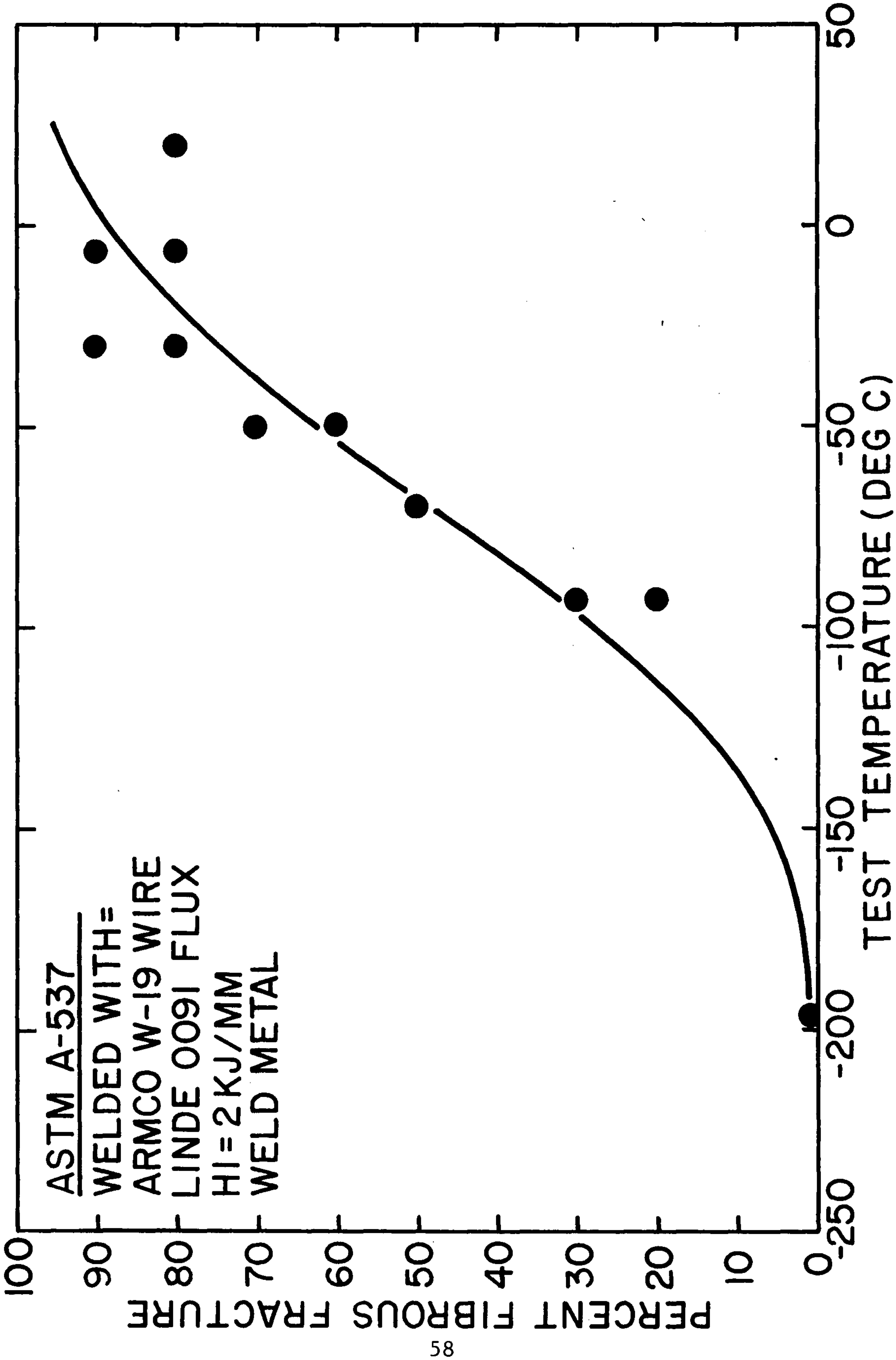
ASTM A-537
WELDED WITH=
ARMCO W-19 WIRE
LINDE 0091 FLUX
HI=2KJ/MM
WELD METAL
PERCENT FIBROUS FRACTURE
100
90
80
70
60
50
40
30
20
10
0
-250
-200
-150
-100
-50
0
50
TEST TEMPERATURE (DEG C)

FIGURE 2c.

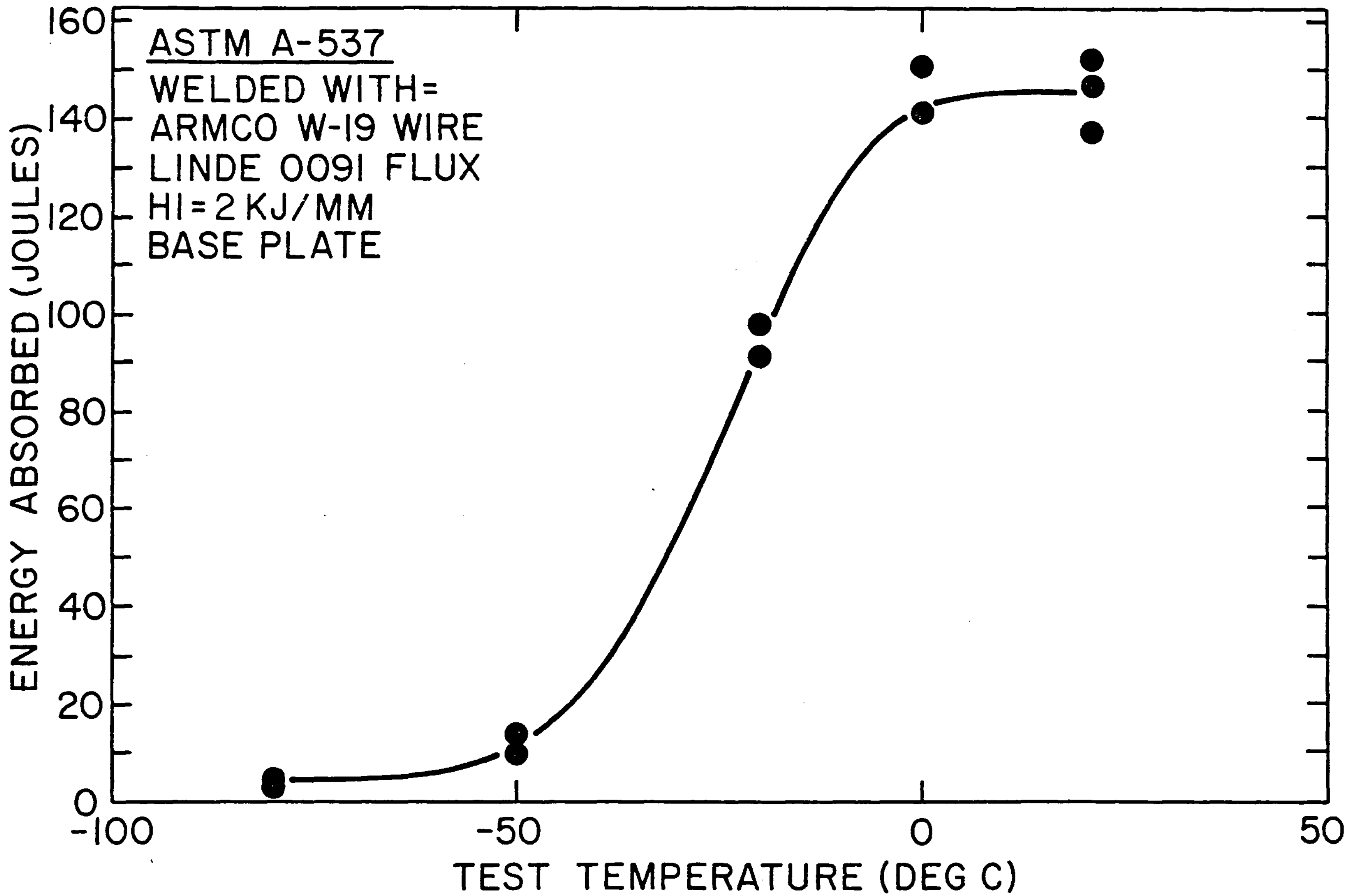
ASTM A-537
WELDED WITH=
ARMCO W-19 WIRE
LINDE 0091 FLUX
HI=2 KJ/MM
BASE PLATE
ENERGY ABSORBED (JOULES)
160
140
120
100
80
60
40
20
0
-100
-50
0
50
TEST TEMPERATURE (DEG C)

FIGURE 3a.

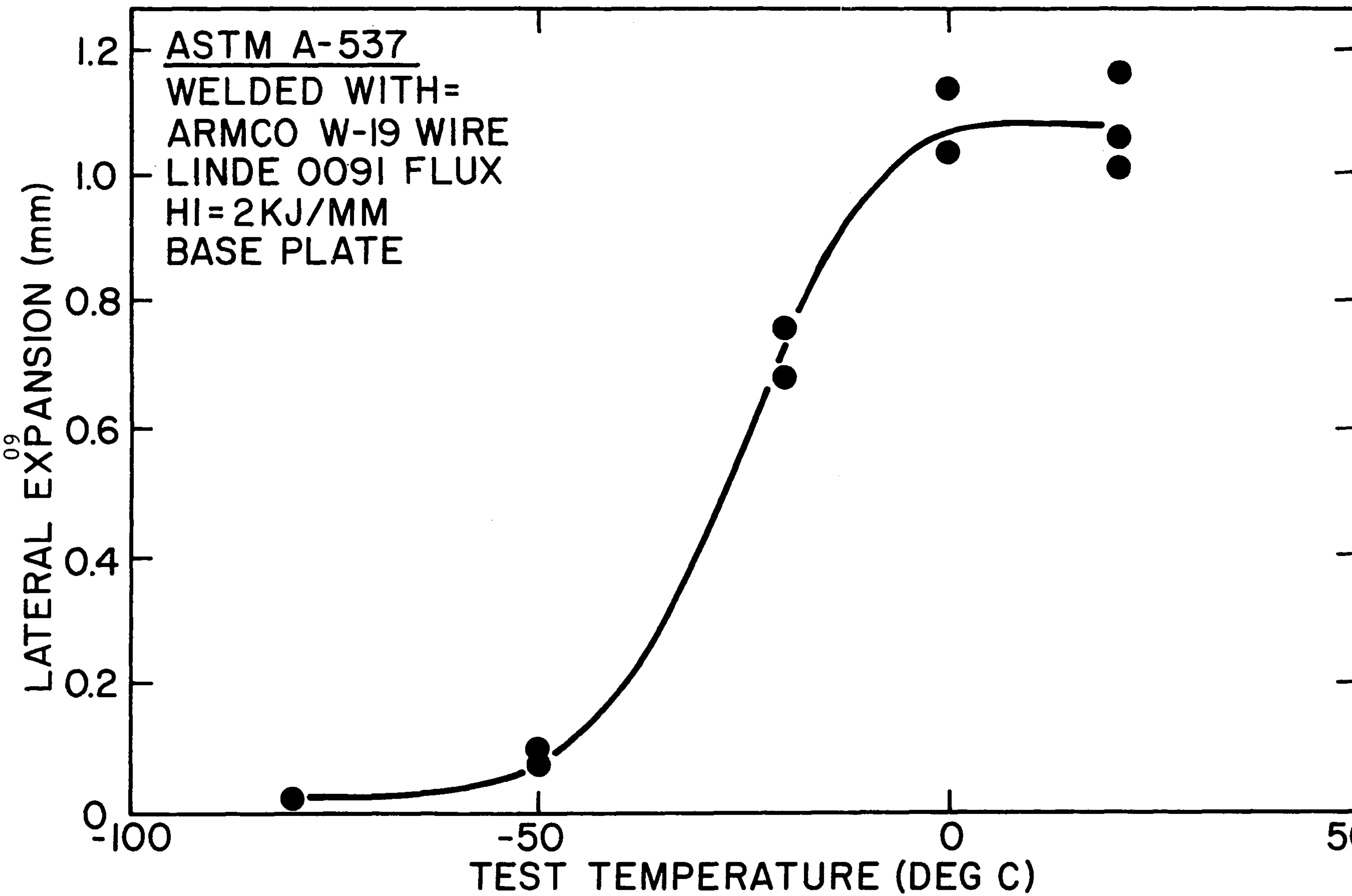
ASTM A-537
WELDED WITH=
ARMCO W-19 WIRE
LINDE 0091 FLUX
HI=2KJ/MM
BASE PLATE
LATERAL EXPANSION (mm)
1.2
1.0
0.8
0.6
0.4
0.2
0
-100
-50
0
50
TEST TEMPERATURE (DEG C)

FIGURE 3b.

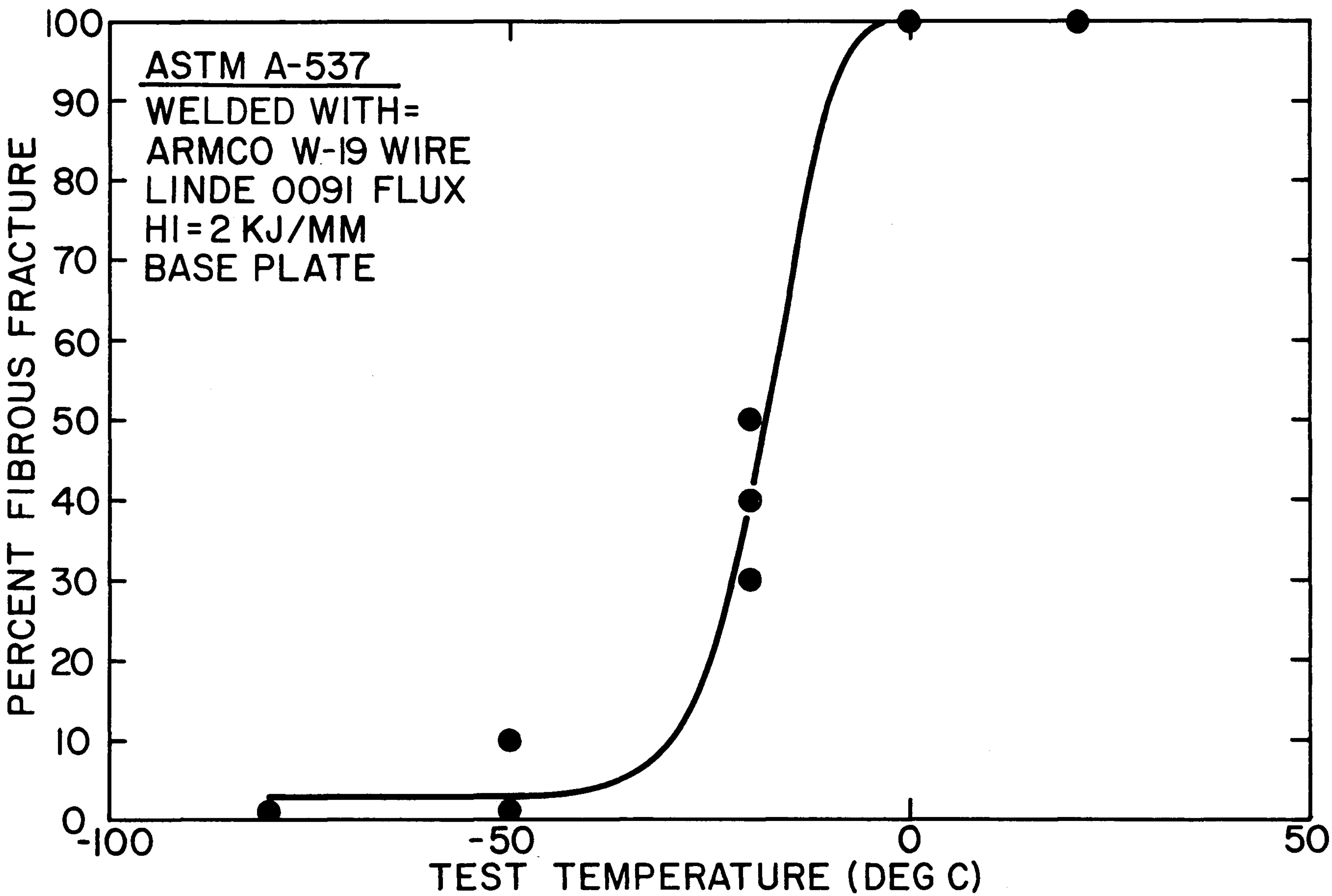
ASTM A-537
WELDED WITH=
ARMCO W-19 WIRE
LINDE 0091 FLUX
HI = 2 KJ/MM
BASE PLATE
PERCENT FIBROUS FRACTURE
0
10
20
30
40
50
60
70
80
90
100
-100
-50
0
50
TEST TEMPERATURE (DEG C)

FIGURE 3c.

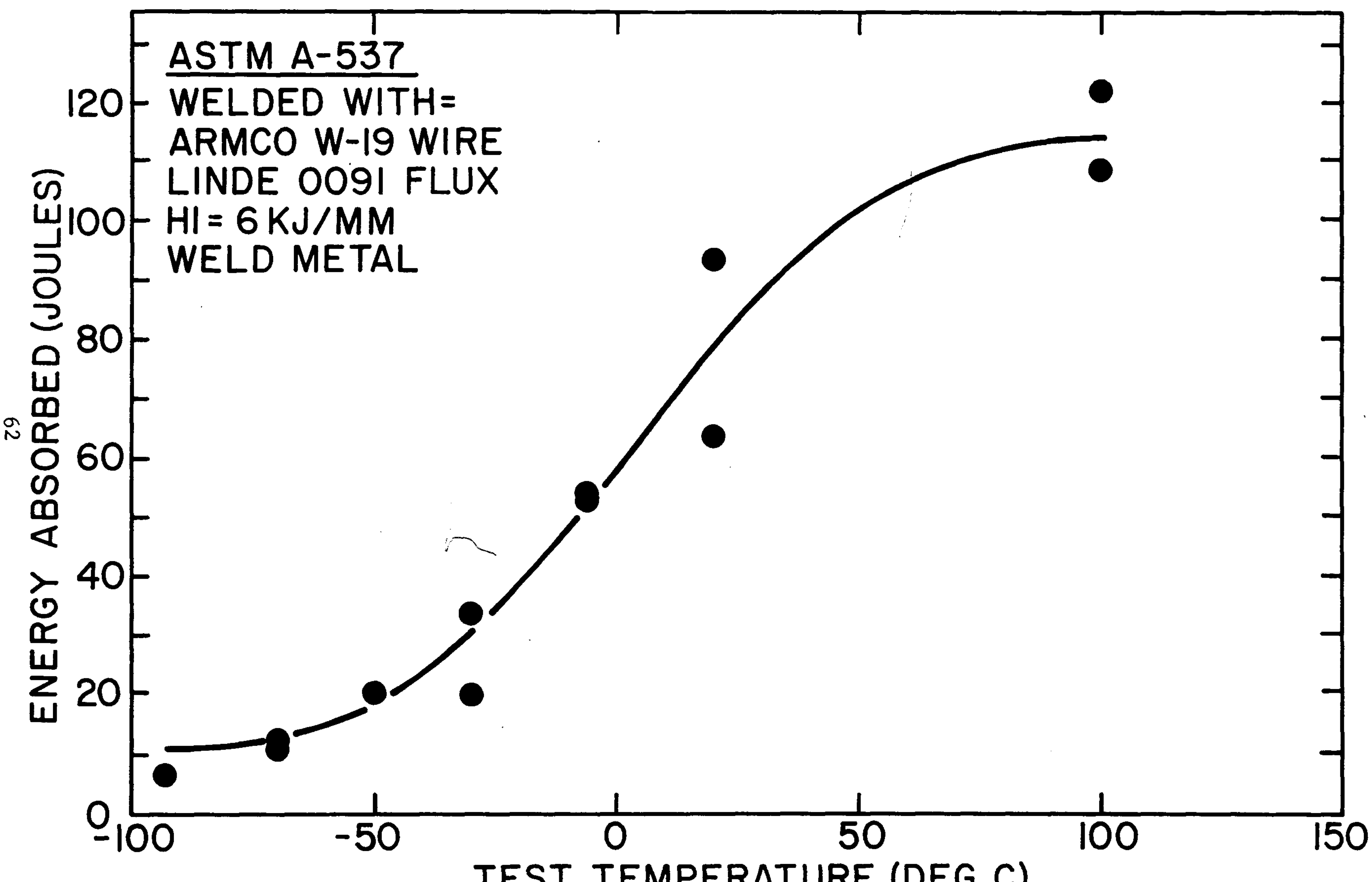
ASTM A-537
WELDED WITH=
ARMCO W-19 WIRE
LINDE 0091 FLUX
HI = 6 KJ/MM
WELD METAL
ENERGY ABSORBED (JOULES)
0
20
40
60
80
100
120
-100
-50
0
50
100
150
TEST TEMPERATURE (DEG C)

FIGURE 4a.

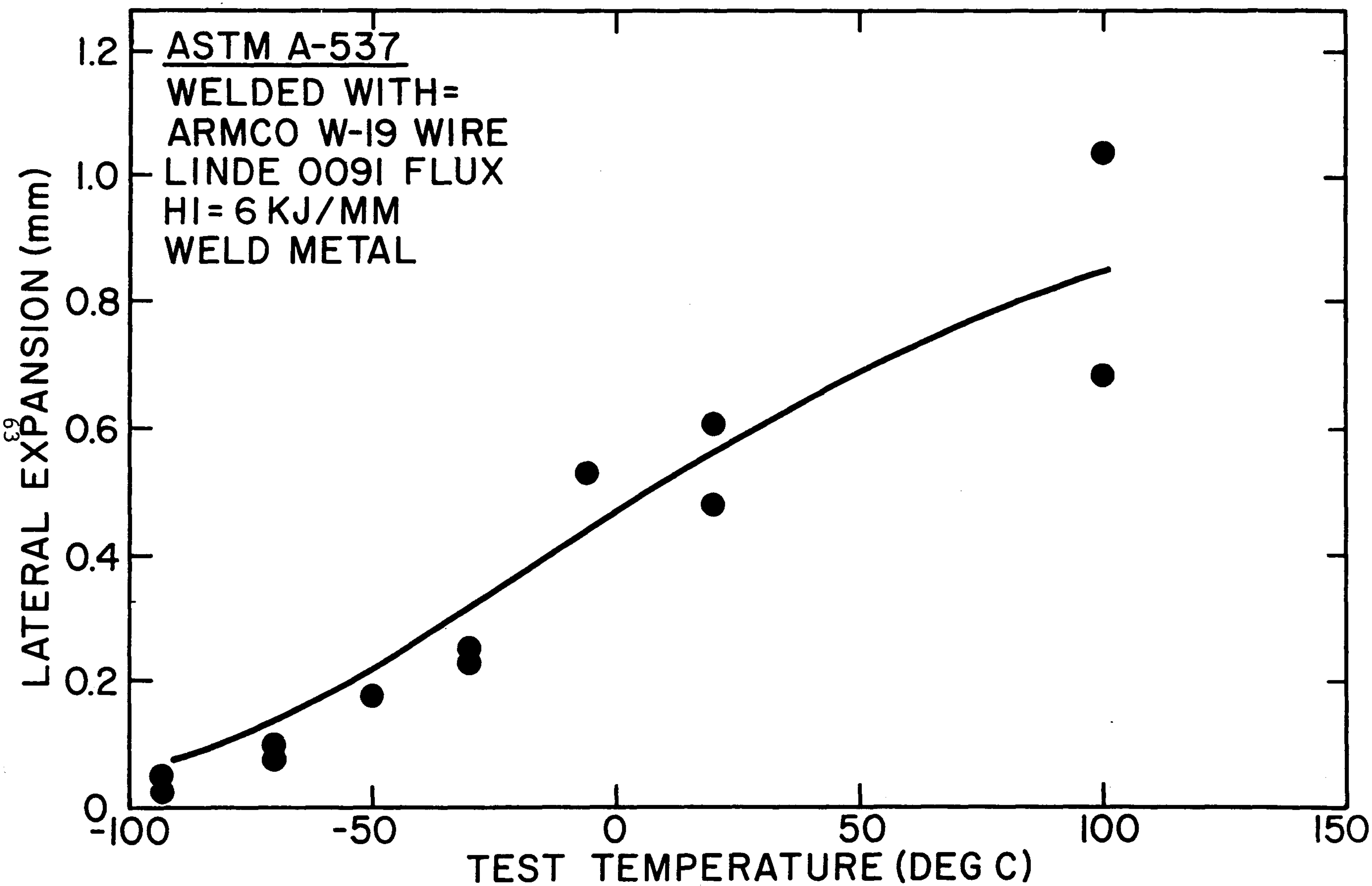
ASTM A-537
WELDED WITH=
ARMCO W-19 WIRE
LINDE 0091 FLUX
HI = 6 KJ/MM
WELD METAL
LATERAL EXPANSION (mm)
0
0.2
0.4
0.6
0.8
1.0
1.2
-100
-50
0
50
100
150
TEST TEMPERATURE (DEG C)

FIGURE 4 b.

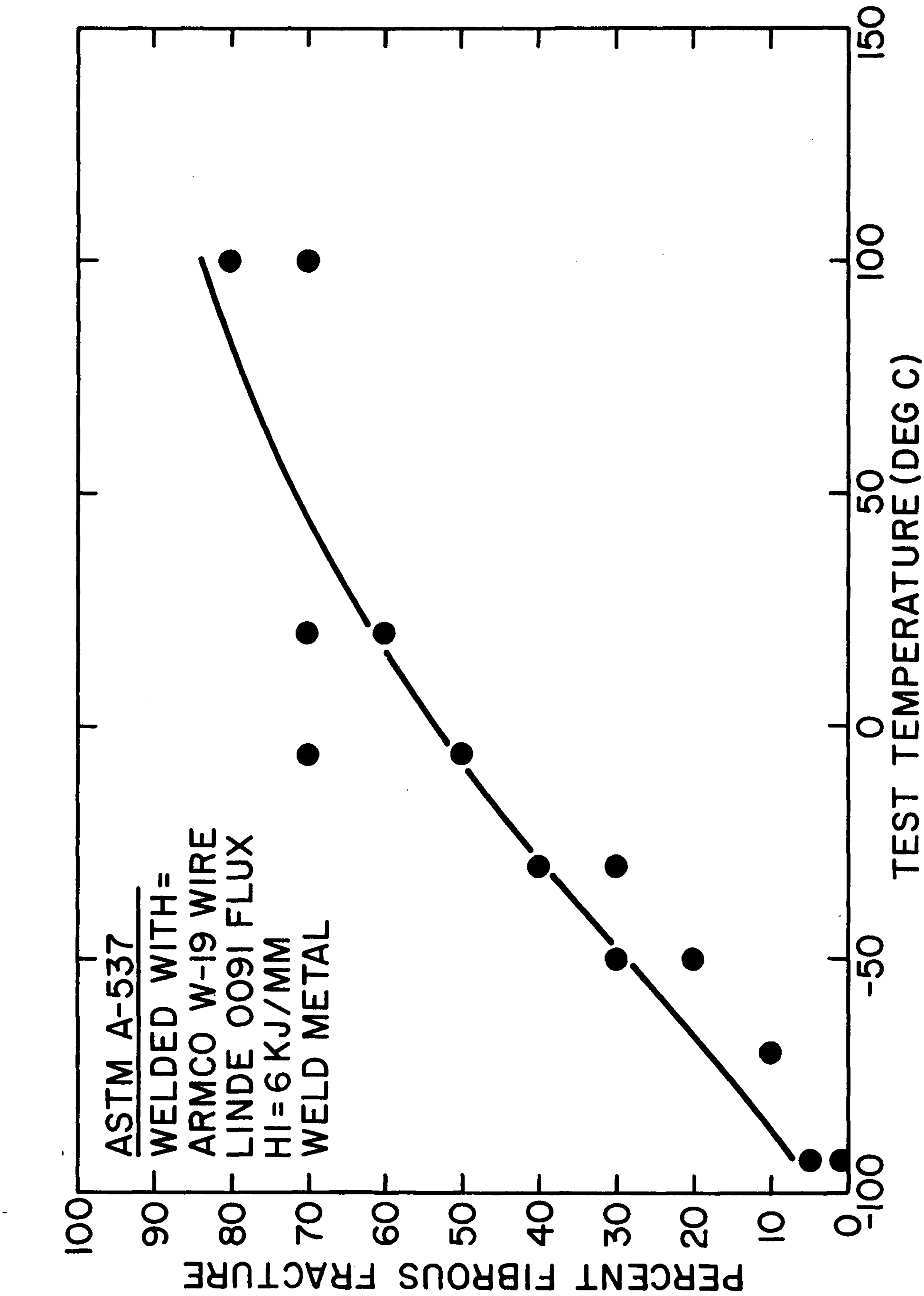
ASTM A-537
WELDED WITH=
ARMCO W-19 WIRE
LINDE 0091 FLUX
HI=6 KJ/MM
WELD METAL
PERCENT FIBROUS FRACTURE
0
10
20
30
40
50
60
70
80
90
100
-100
-50
0
50
100
150
TEST TEMPERATURE (DEG C)

FIGURE 4c.

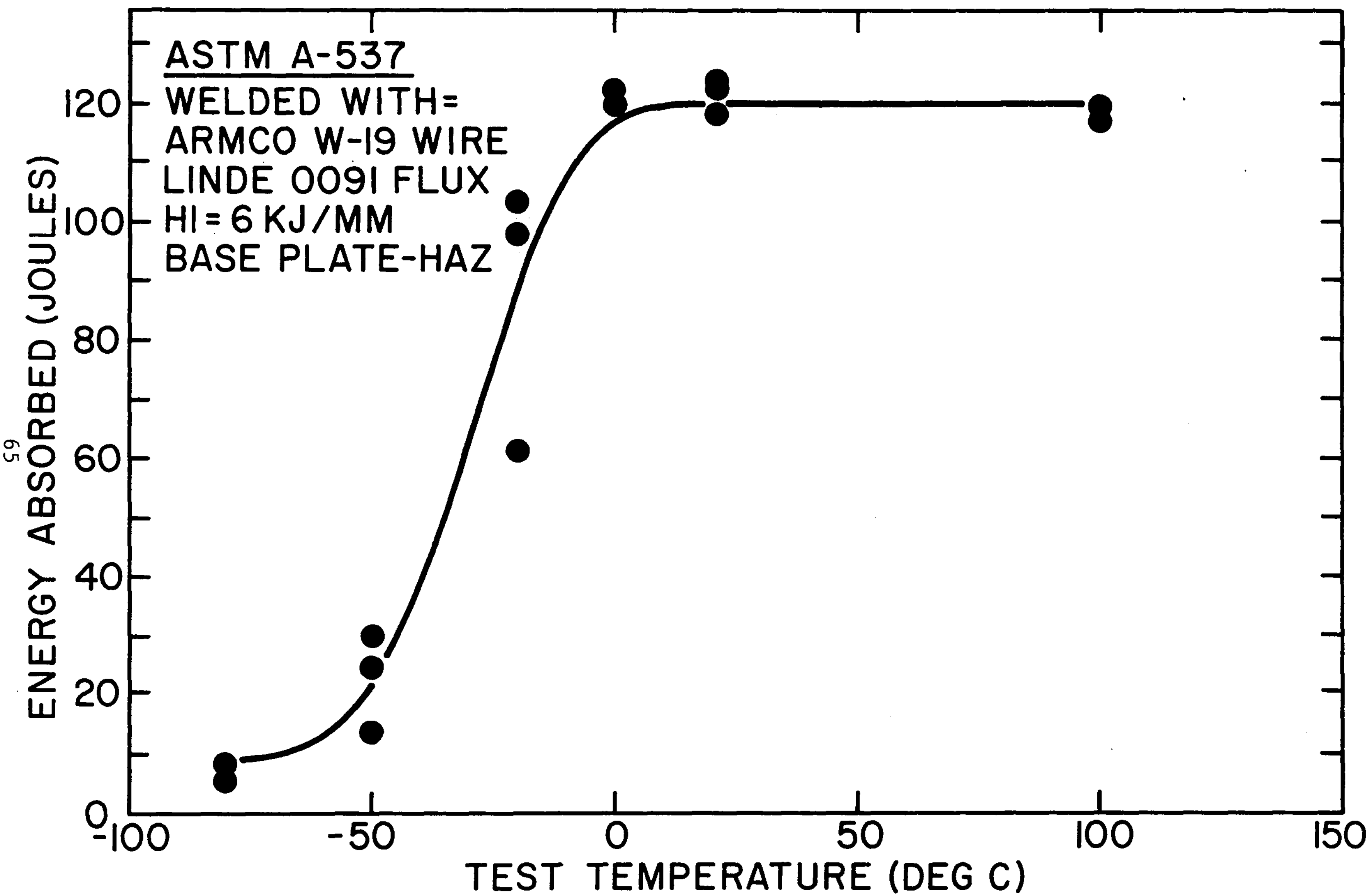
ASTM A-537
WELDED WITH=
ARMCO W-19 WIRE
LINDE 0091 FLUX
HI = 6 KJ/MM
BASE PLATE-HAZ
ENERGY ABSORBED (JOULES)
0
20
40
60
80
100
120
-100
-50
0
50
100
150
TEST TEMPERATURE (DEG C)

FIGURE 5a.

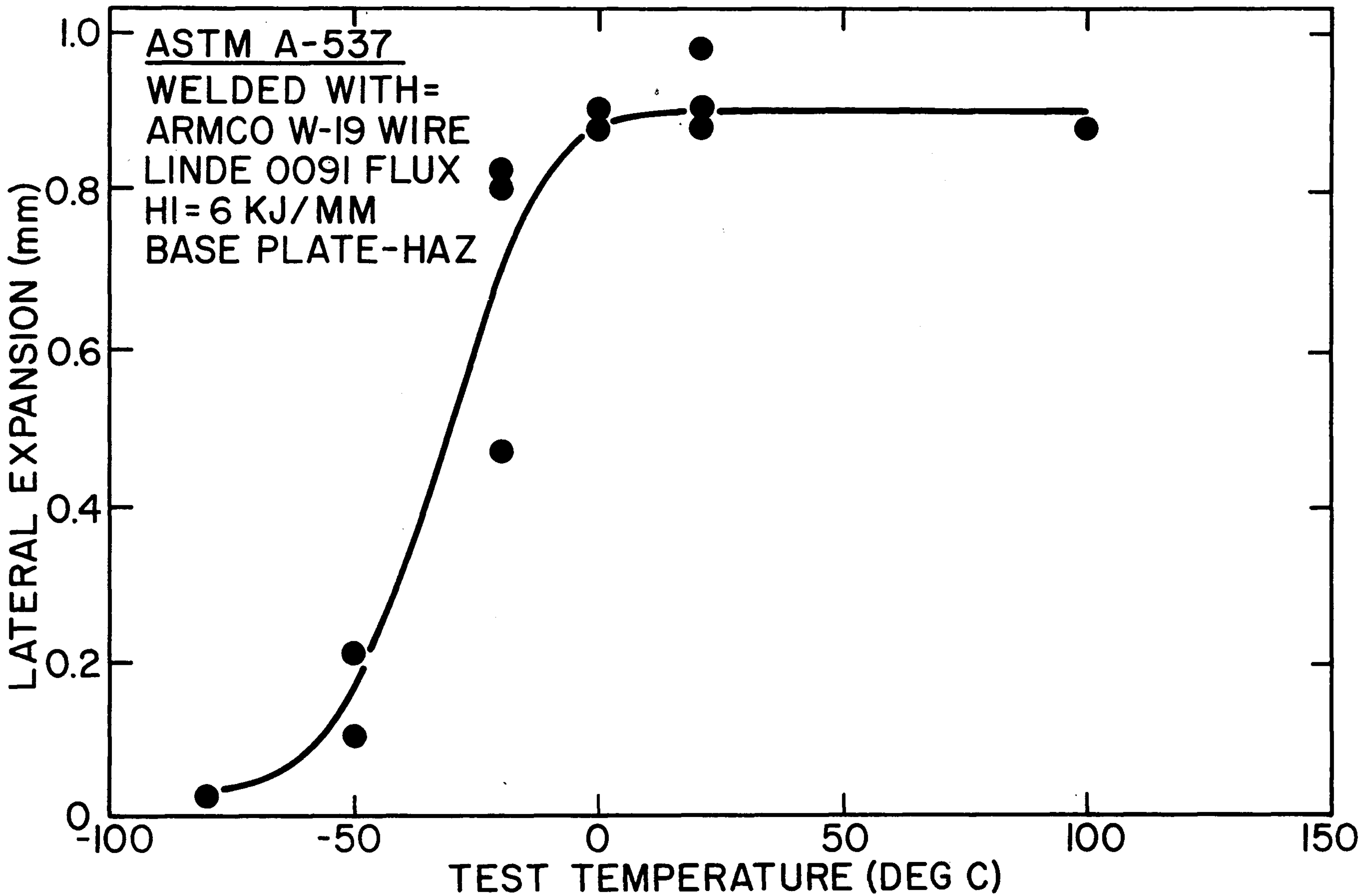
ASTM A-537
WELDED WITH=
ARMCO W-19 WIRE
LINDE 0091 FLUX
HI=6 KJ/MM
BASE PLATE-HAZ
LATERAL EXPANSION (mm)
1.0
0.8
0.6
0.4
0.2
0
-100
-50
0
50
100
150
TEST TEMPERATURE (DEG C)

FIGURE 5b.

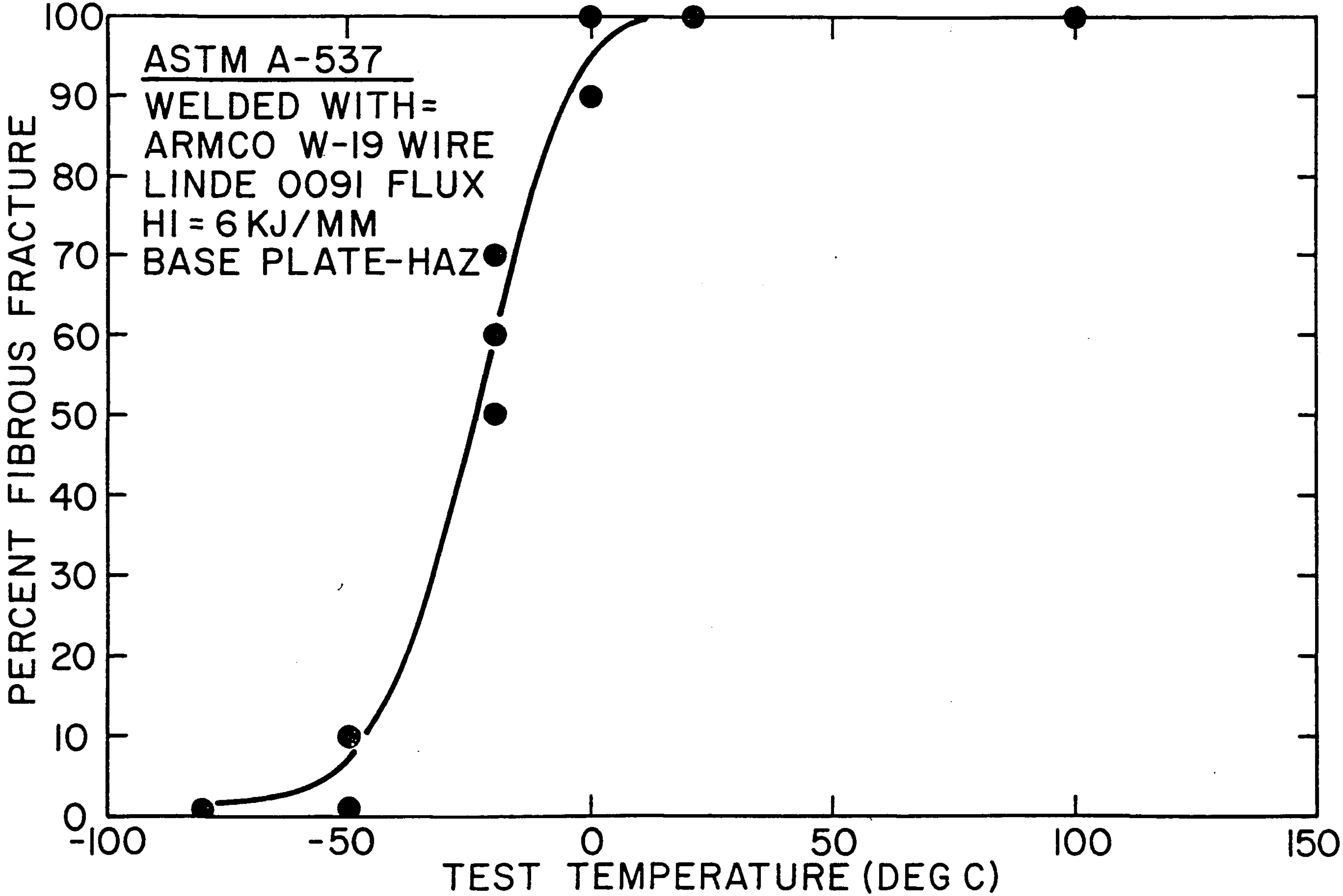
ASTM A-537
WELDED WITH=
ARMCO W-19 WIRE
LINDE 0091 FLUX
HI = 6 KJ/MM
BASE PLATE-HAZ
PERCENT FIBROUS FRACTURE
100
90
80
70
60
50
40
30
20
10
0
-100
-50
0
50
100
150
TEST TEMPERATURE (DEG C)

FIGURE 5c.

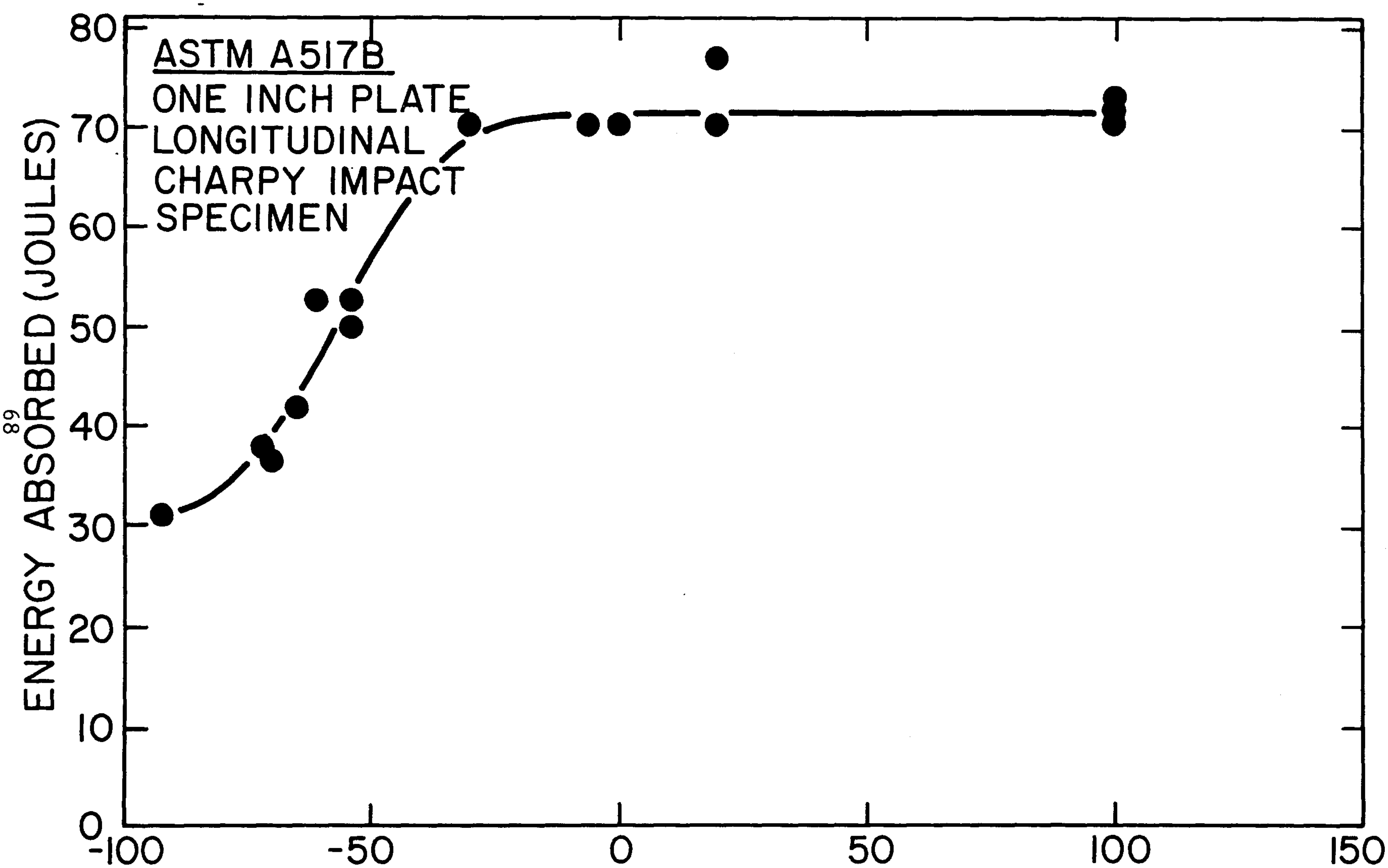
ASTM A517B
ONE INCH PLATE
LONGITUDINAL
CHARPY IMPACT
SPECIMEN
ENERGY ABSORBED (JOULES)
TEST TEMPERATURE (DEG C)
0
10
20
30
40
50
60
70
80
-100
-50
0
50
100
150

FIGURE 6a.

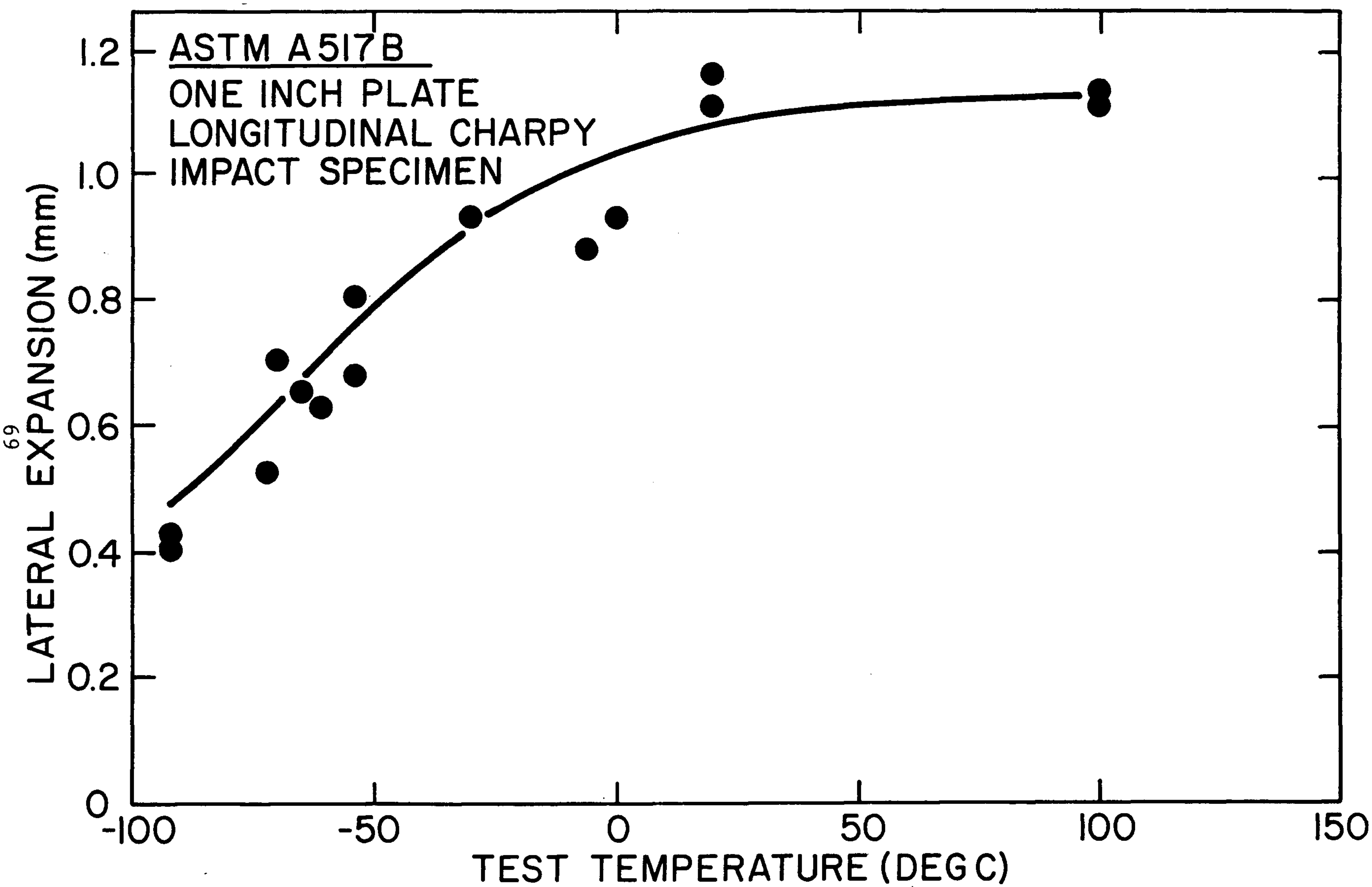
ASTM A517B
ONE INCH PLATE
LONGITUDINAL CHARPY
IMPACT SPECIMEN
LATERAL EXPANSION (mm)
0
0.2
0.4
0.6
0.8
1.0
1.2
-100
-50
0
50
100
150
TEST TEMPERATURE (DEG C)

FIGURE 6b.

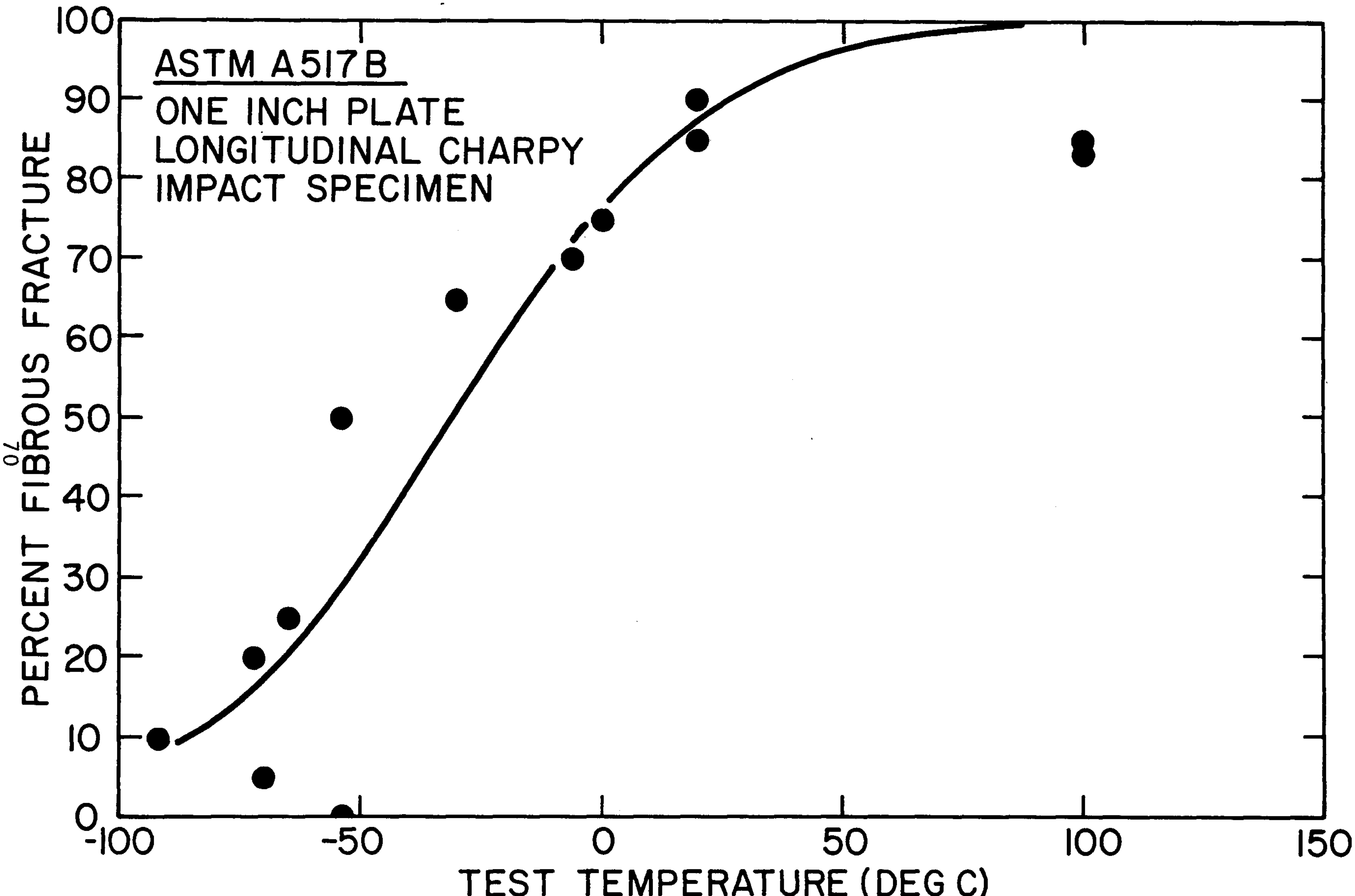
ASTM A517B
ONE INCH PLATE
LONGITUDINAL CHARPY
IMPACT SPECIMEN
PERCENT FIBROUS FRACTURE
0
10
20
30
40
50
60
70
80
90
100
-100
-50
0
50
100
150
TEST TEMPERATURE (DEG C)

FIGURE 6c.

APPENDIX 2

Stress Analyses on Four Point Bending

From Figure 4 the stresses are given by:

$$\sigma_{ZZ} = \frac{M}{I}\left(\frac{t}{2} - y\right)$$

and

$$M = \frac{P}{2} \times L_1 \qquad I = \frac{W\ t^3}{12}$$

where

M = applied moment

t = thickness

I = moment of inertia

W = width

P = applied load

L_1 = (outer span - inner span)/2

$$\sigma_{ZZ} = \frac{6\ P \times L_1}{W \times t^3}\left(\frac{t}{2} - Y\right)$$

and the stresses for the outer tension fiber (Y = 0)

$$\sigma_{ZZ} = \frac{3\ P \times L_1}{W\ t^2}$$

When

$$\sigma_{ZZ} = \sigma_{YS}$$

$$\sigma_{YS} = \left(\frac{3\ L_1}{W\ t^2}\right) P_a$$

For the composite material:

$$\sigma_{YS_{M_1}} = \left(\frac{3\ L_1}{W\ t^2}\right) P_{a_1}$$

$$\sigma_{YS_{M_2}} = \left(\frac{3\ L_1}{W\ t^2}\right) P_{a_2}$$

$$\sigma_{YS_{M_3}} = \left(\frac{3\ L_1}{W\ t^2}\right) P_{a_3}$$

$$\sigma_{YS_{M_1}} < \sigma_{YS_{M_2}} < \sigma_{YS_{M_3}}$$

$$P_{a_1} < P_{a_2} < P_{a_3}$$

APPENDIX 3

Stress-intensity factors for semi-elliptical surface flaws under linearly varying load

$$K_I = M_B \frac{Po\sqrt{\pi}}{E(K)} \quad \frac{b}{a} \quad a^2 \sin^2 \theta + b^2 \cos^2 \theta \quad ^{1/4}$$

expressed with the nomenclature used in this work:

$$K_I = M_B\ \sigma_a \frac{\sqrt{\pi\, b}}{E(K)} \quad \frac{a^2 \sin^2 \theta + b^2 \cos^2 \theta}{a^2} \quad ^{1/4}$$

$$K_I = M_B\ \sigma_a \frac{\sqrt{\pi\, b}}{E(K)} \quad \sin^2 \theta + \frac{b^2}{a^2} \cos^2 \theta \quad ^{1/4}$$

$E(k)$ = complete elliptical integral of the second kind

k = modulus of Jacobian elliptic function

$$k = 1 - \frac{b^2}{a^2}$$

$$\sigma_a = \frac{3\ P \times L_1}{W\ t^2}$$

σ_a = stresses in the outer tension fiber

$$K_I = M_B \left(\frac{3\ P \times L_1}{W\ t^2}\right) \frac{\sqrt{\pi b}}{E(K)} \quad \sin^2 \theta + \frac{b^2}{a^2} \cos^2 \theta \quad ^{1/4} \qquad (6)$$

Example of application of equation (6) to the four point bend specimen notched.

specimen material: A517B

test temperature: -80°C

load: 391 Kn

2a: 86.995 mm

a: 43.4975 mm

b: 8.890 mm

L_1: 155.575 mm

W: 228.6 mm

t: 25.4 mm

$\theta = 10°$

and for:

$$k = 1 - \frac{b^2}{a^2} = 0.96$$

$$\sin \emptyset = 0.96$$

$$\emptyset = 74°$$

The complete elliptic integrals are tabulated in ref. (23)

$$E_{(K)} = 1.0844$$

From Fig. 13 for

$$\sigma = 10° \qquad M_B = 0.90$$

$$\frac{b}{a} = 0.20$$

introducing the values in eq. (6), it gives:

$$K_I = 87.36 \text{ MPa}\sqrt{m}$$

VITA

Ruben Alejandro Espinosa, son of Luis Espinosa and Elina Bucheli, was born in Quito, Ecuador on December 6, 1943. He graduated from Escuela Politecnica Nacional of Quito, Ecuador in 1968 and from Institut Politechnique de Grenoble, France in 1970.

Following graduation, Mr. Espinosa was employed as a Maintenance Engineer in the "Empresa de Cemento Chimborazo" and since 1974 he is currently working for the Escuela Politecnica Nacional as a Research Engineer.

In January 1975, Mr. Espinosa entered the Graduate School of Lehigh University where he pursued a program of graduate study in the Department of Metallurgy and Materials Science.

Mr. Espinosa is a member of the American Society for Metals and the American Welding Society.